# MODELLING UPLAND RUNOFF PATTERN USING GEOGRAPHIC INFORMATION SYSTEM - A CASE STUDY OF YUEN LONG - KAM TIN CATCHMENTS, NEW TERRITORIES, HONG KONG

by

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Thesis submitted to the Graduate School
of the Chinese University of Hong Kong
in partial fulfilment of the requirements
for the degree of Master of Philosophy

December 1994

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# ACKNOWLEDGEMENT

My thanks are due to all who have assisted in many ways. I would like to acknowledge gratefully, the help and supervision kindly given by Dr. T. Fung, lecturer of the Geography Department, Chinese University of Hong Kong. Much thanks are also given to Dr. Ian Jackson and Dr. A.J. Brimicombe for invaluable advice on hydrology and geographic information system respectively.

I must also express my gratitude to the Hong Kong Polytechnic University for the funding of this programme and the various government departments for providing data and assistance. They are the Survey and Mapping Office, Geotechnical Control Office, Water Supplies Department, Royal Observatory, Drainage Services Department and Agriculture and Fisheries Department.

In addition, I am much indebted to the technical advice and help of my colleagues and friends in the Polytechnic. Above all, I would like to dedicate all those efforts to Kin Shing, Keith, my mother and especially to my father who has just left us to a world free of sufferings and pain.

Lilian, S.C. CHENG

December 1994

## ABSTRACT

Floods in Hong Kong cause one of the more serious problems in land management. Significant floods are being experienced in the low-lying areas of rural districts in the New Territories, and in particular the north and northwestern parts which accounts for 65% of Hong Kong's river flood plain areas. In spite of the short duration of most flood events, the flashy and intense rainfall pattern together with shallow and short-routed upland stream channels all contribute to large volume of fast-following surface runoff at one time to the upland/lowland frontier. To handle the problem in a wider scope, spatio-temporal pattern of surface flow and flood hydrology of upland catchments need to be examined in a more comprehensive way.

Based on Clark's unit hydrograph method which parallels the time-area approach, catchment isochrones, ie. lines of equal concentration time of storm runoff above the 40-metre contour are derived for the study area. This necessitates a detailed survey of the local terrain and

hydrological parameters of stream channels including surfacelength and slopes. In this context, the Geographic Information System has been powerful in capturing, editing and manipulating parameters useful for inputting into the deterministic hydrologic model. Results show that it only takes about 30 minutes for surface runoff from the farthest stream source to reach the lowland frontier. More rapid flows occur in areas with steeper slopes, shorter surfacelength and more rectangular drainage pattern.

In addition, areas bounded by and in between the isochrones would readily be used to estimate the amount of total overland stormflow for every unit time of any storm pattern input. Unit hydrographs of five storms are produced by the model based on their 5-minute interval rainfall data. By comparing with hydrographs produced by stream-gauges, modelling with more severe storms like Typhoon Brenda and Gordon can give a better approximation of shape and runoff volume. Provided with more information or research on runoff abstraction, the time-area hydrologic model can apply well to runoff routing in small catchments of Hong Kong. In conclusion, in cases where data are found totally insufficient or unavailable for detail hydraulic modelling, this study has shown the possibility of estimating surface runoff volume in time and space using simple parameters for hydrologic modelling.

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# TABLE OF CONTENTS

Page

## LIST OF FIGURES

# LIST OF TABLES

## LIST OF APPENDICES

# CHAPTER 1 INTRODUCTION

Floods in Hong Kong pose a major hazard, causing destruction and loss in property, particularly farm produce. A critical combination of heavy rainfall, averaging about 2,200 mm per annum, and an abnormal rise in sea level as a result of storm surges especially during typhoons often bring along severe flooding. May to September are the months most prone to flooding. Significant flood problems are acute especially in the low-lying rural areas in the northwestern part of the New Territories. It is estimated that 65% of Hong Kong's total 5,000 hectares of river floodplains lie in the north and northwestern parts of the New Territories (Mott McDonald HK Ltd., 1989). Here, large stretches of lowland are reclaimed from former inter-tidal mud flats and coastal marshes, resulting in significant inundation during tidal storm surges. In the past five years or so, the Government has spent much effort in flood prevention or minimising the risk to the lowland area (Mott McDonald HK Ltd., 1989). These include an extensive topographic survey, planned construction or extension of culverts, weirs and numerous drainage systems, taking legal actions against abuse or misuse of rural land as well as cooperation with the Shenzhen authority on the issue of combating flooding. Nevertheless, the steep upland regions with shallow and short-routed channels which cause extremely rapid and concentrated flow to the lowlands have always been overlooked. As most of these areas are not of major economic concern, not many investigations have been carried out on topography, hydrology and meteorology of the uplands for the last few decades. Large-scale map sheets are not revised as frequently as the lowland ones and except the Tai Mo Shan, no other upland rain gauges of any kind is installed.

For many years in the past, tackling flood events was based on just a crisis management approach (Mott McDonald HK Ltd., 1989). Whenever serious floods occurred, maintenance of affected drains, roads etc. would be looked after by the Highways Department; loss of property and livestock of farmers would be taken care by the Agriculture and Fisheries Department. Such emergency activities were in fact only one aspect of a comprehensive flood loss prevention and management scheme. Other more important aspects like flood plain management, retarding runoff in upriver catchments and improvements in dikes, channels, floodways should be dealt with in a well-integrated or more coordinated way by the Government. With such objectives in mind, the Drainage and Services Department was set up in 1987 to unify the responsibilities for main drainage system management. Legislative power under a proposed Drainage Ordinance has also been passed to enable the Government to achieve comprehensive maintenance of watercourses within Government and private lands.

Nevertheless, before any structural and non-structural measures are to be adopted to combat flooding, a thorough quantitative and scientific study of flood prone and adjacent areas is deemed necessary, so that any measures taken would be rational and cost-effective, acceptable to both the users (dwellers, private developers) and the Government. This calls for an extensive field data collection, sophisticated computational hydrological-hydraulic modelling for flood-flow analysis and any possibility of accurate real-time flood forecasting and alarm systems. In this aspect, the Geographic Information System may be regarded as a powerful tool in handling large amount of data, integrating data from various sources and formats as well as performing fast and accurate analyses for a wide scope of application.

## 1.1 Objectives

In view of the above inadequacies performed by the local authority, it is hoped that this study could look into greater areas and provide more information concerning stormflow based on the following major objectives:

(a) to provide a topographic database using Geographic Information System and evaluate its applicability in hydrological modelling;

(b) to study the spatial and temporal pattern of stormflow in the upland catchments delimited by the 40-metre contour; and

(c) to apply and evaluate the time-area method in modelling flow pattern in small catchments.

## 1.2 The Study Area

Among a total of 25 drainage basins in Hong Kong defined by the Drainage Services Department, drainage basin no.9, the Kam Tin and Yuen Long areas in the northwestern part of the territory is selected as the study area (Figure 1.1). It consists of four major catchment areas. Streams in the Shek Kong Catchment at the southeast portion drain the slopes of Kai Kung Leng (370 metres), Tai To Yan (565 metres) and western slopes of the highest peak, Tai Mo Shan (957 metres) in a westerly to northwesterly direction. Both the Yuen Long and Shek Po Tsuen catchments lie on granitic terrain, and with major flow paths drain northwards to account for the frequent flooding and inundation to the Yuen Long and Kam Tin area, the largest piece of lowland in Hong Kong. Finally, the Ngau Tam Mei Catchment, being the smallest, is located at the northern part of the study area, draining the northern slopes

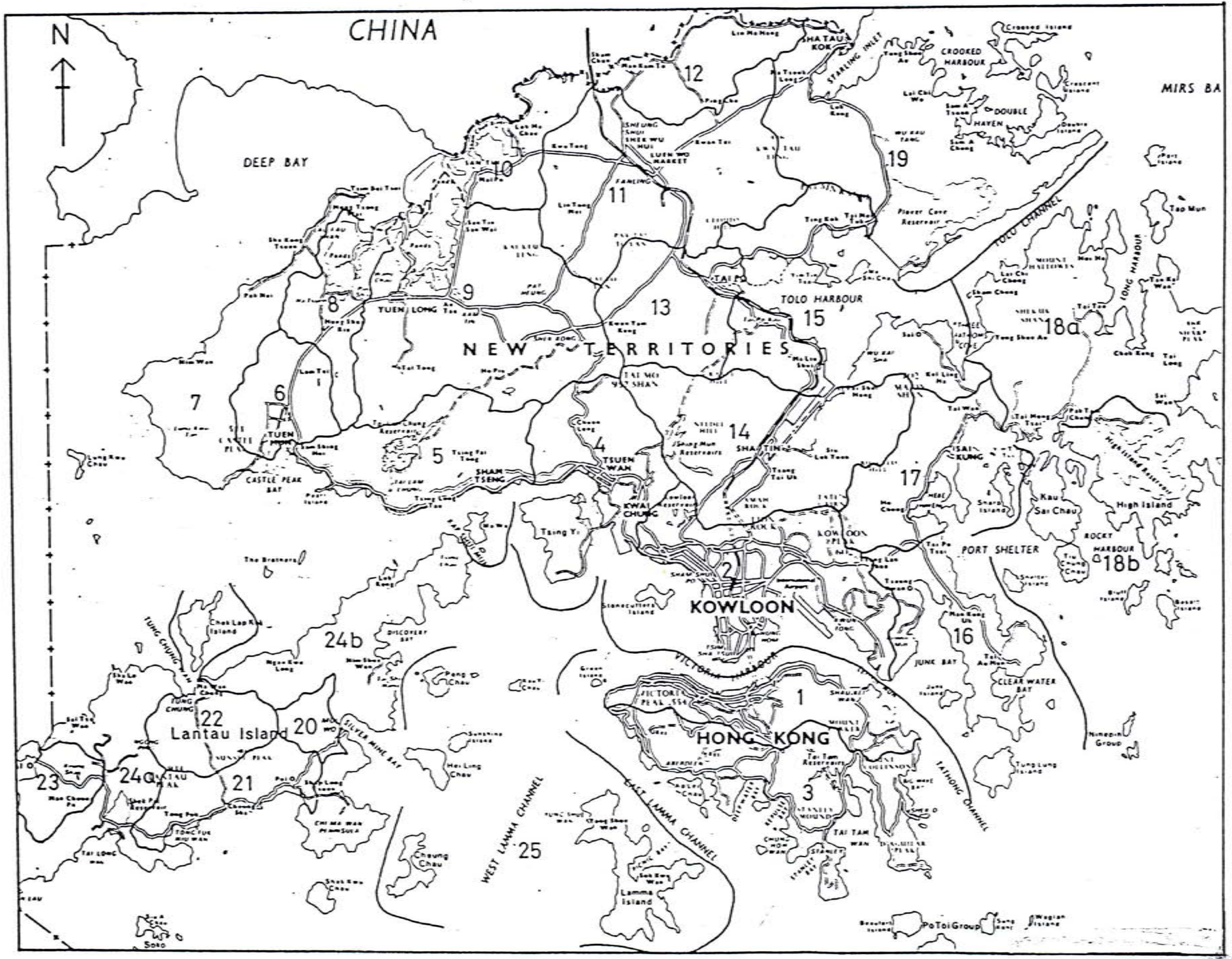


Figure 1.1 Drainage Basin Boundaries of Hong Kong. Source: Drainage Services Department.

of Kai Kung Leng to a westerly direction (Figure 1.2). Within the whole drainage basin, streams are numerous and short-routed, running essentially from east to west and eventually finding the outlet to Deep Bay. With the exception of rectangular drainage pattern near the Tai Lam Chung area in the south, most belong to dendritic ones. A sharp break of slope might be found at around 40-metre elevation. Above that stream networks are well-identified in an orderly pattern where human intervention is scarce and artificial drainage constructions are few. On the contrary, the downstream portion to the lowland consists of numerous criss-cross streamlets. In addition to the artificial drainage and irrigation ditches so far constructed and interfered due to changing land uses, the overall drainage pattern is regarded as confusing and not easily identifiable.

This drainage basin is so chosen because of two main reasons. Physically, being the largest plain in Hong Kong, it frequently suffers from flooding during typhoons or rainstorms, causing extreme inconvenience to daily life as exemplified in the following section. Economically, it is a place of constantly changing land use in this decade, especially in reclaiming huge stretches of fish ponds for non-rural purposes. The reduction in fish ponds have aroused both the Government

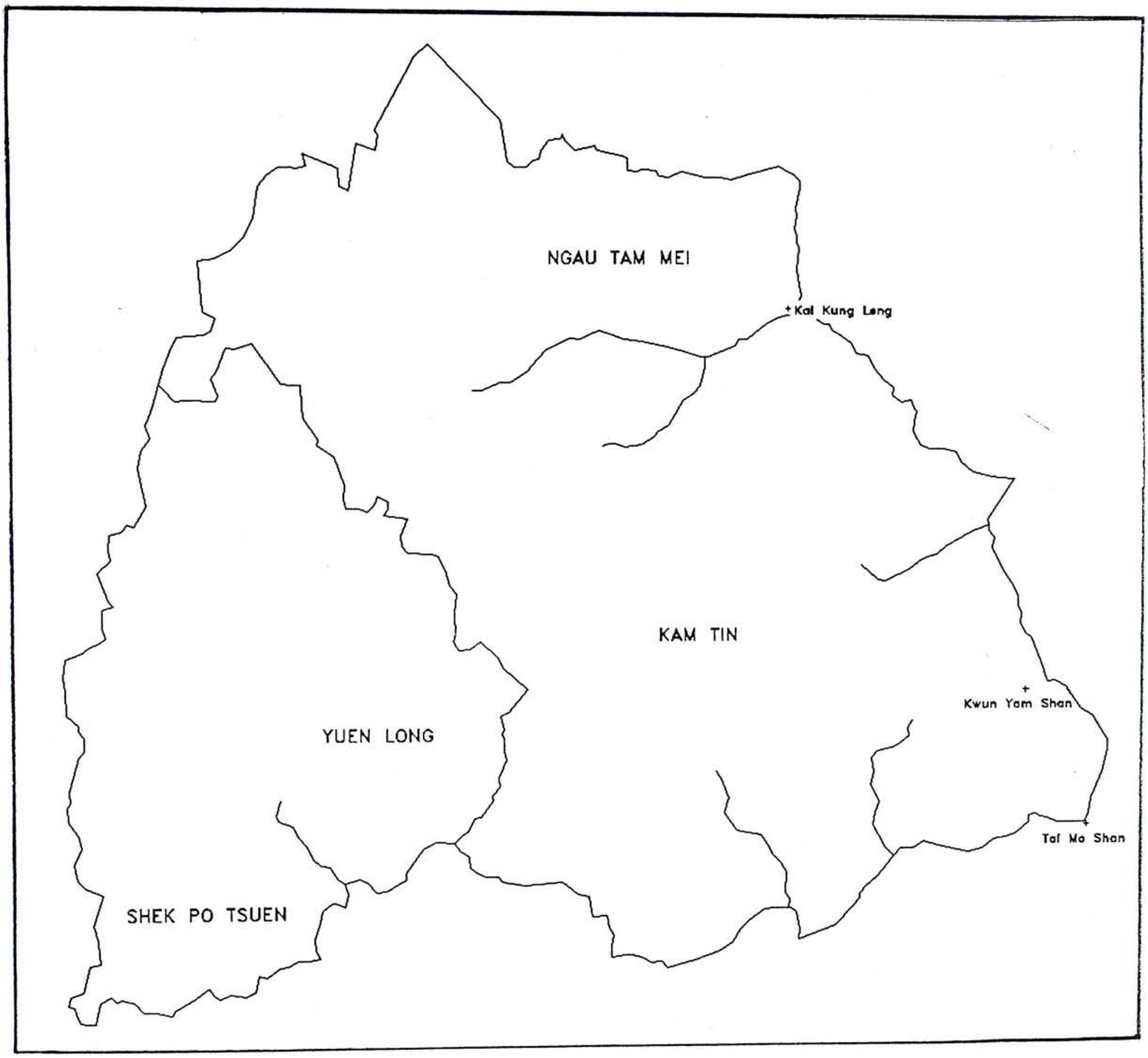


Figure 1.2 Major catchment and subcatchment boundaries.
Source : Drainage Services Department.

and public concern of aggravating the flood condition, thus calling upon the need for more expertised investigation into flood and land management. In this study, although the topographic database is built for the entire drainage basin, modelling and analysis will only be performed for the upland catchments as stream networks are simpler and surface flow involves fewer parameters while excluding coastal tidal effect. More importantly, this is the part where records of past studies are scarce and often neglected.

## 1.3 Studied Typhoons

Typhoons or tropical cyclones are considered the most direct and severe cause of flooding in Hong Kong. Rain comes mostly in summer, during which the passage of typhoons brings significant amount of rainfall, especially for those associated with stationary troughs. Nevertheless, as records of consistently short time intervals are required for the modelling, only typhoons from the last five years are selected as both automatic rain and stream gauge data are then available for every 5-minute interval.

Rainfall records from five typhoons are brought under study. Three of which, Typhoon Brenda (16-21 May 1989), Typhoon Gordon (11-19 July

1989) and Typhoon Tasha (16-21 August 1993) reached gale force and storm signal no. 8 was hoisted. Rainfall intensity was great and distribution was uneven, over 500 mm (about 25% of the annual mean) from Brenda and 200 mm from Tasha were brought to the Kam Tin and Shek Kong areas. Damage was great in particular during the passage of Brenda - 100 cases of landslides and 118 floods, mudslides, inundation of 190 hectares of farmland, loss of livestock and an estimated economic loss of $6 million at that time. Although both Gordon and Tasha brought less rain to the northwestern part of the New Territories, numerous cases of flooding were still experienced (Royal Observatory, 1989, 1993).

The other two typhoons - Nathan (15-19 June 1990) and Tasha (27-31 July 1990) were comparatively milder. Only signal no. 3 was hoisted. Rain duration was short but intensity is great, about 250 mm from Nathan and 130 mm from Tasha. This was the result of a few showers and isolated thunderstorms associated with the enhanced southwesterlies (Royal Observatory, 1990). All in all, rainfalls of varying magnitude but mostly of short return periods are used to examine the spatial pattern of runoff and to test the applicability of the routing model.

## 1.4 Rain Gauge and Stream Gauge

As early as 1978, automatic rain gage which records data at 15-minute intervals had already been installed. However, those early ones with too simple design often gave rise to false rainfall counts especially during lightning and power shortage. Not until 1987 were these gauges upgraded with the cooperation of Royal Observatory and Geotechnical Control Office, so that the new solar-powered system becomes more reliable and can operate continuously without interruption for at least 24 hours. More importantly, rainfall data of 5-minute interval can quickly be telemetred through modem to the central stations at the R.O. and G.C.O.. A more detailed explanation of the system structure is reported in Technical Note No. 82 of the Royal Observatory, an automatic rain gauge system.

In the studied upland catchment, only one telemetred automatic rain gauge, N14 operated by the Geotechnical Control Office since June 1983 is found. Hence point depth, ie. rainfall recorded at a point is assumed to apply for the whole area concerned. This gauge is located in a saddle of about 935 metres high near the Tai Mo Shan peak (Figure 1.3). It is an extremely open space where no obstructions of buildings or other structures occur. The 5-minute rain information will serve as input to the

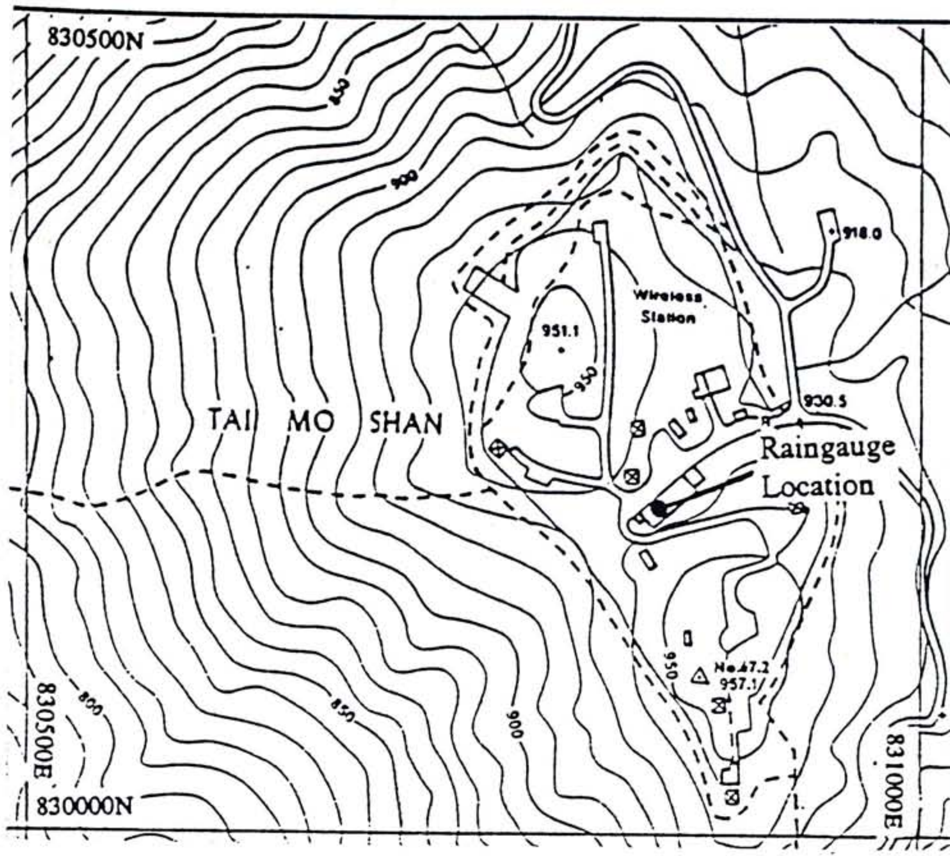


Figure 1.3 Location of N14 rain gauge.
Source : Geotechnical Control Office.

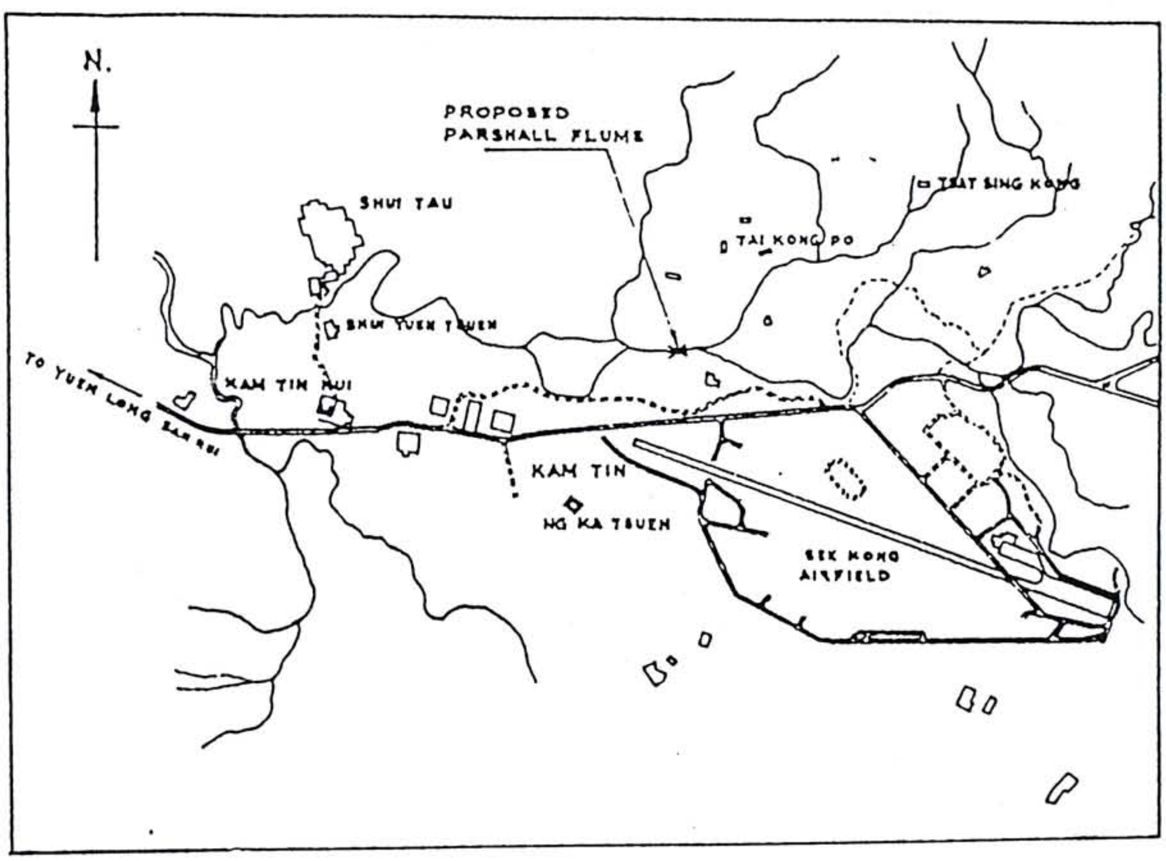


Figure 1.4 Location of Kam Tin stream gauge.
Source : Water Supplies Department.

hydrological modelling. Although records are considered reliable and continuous, as mentioned previously, rain data received are all rounded up to 0.5 mm, implying that more subtle changes in amount will not be available.

Similar to the rain gauge, only one stream gauge, the Kam Tin gauge with more reliable records is found while the Yuen Long Flood Channel `A' and `B' gauges are under reconstruction and are not automated. This Kam Tin lowland stream gauge produces continuous records since July 1964, records streamflow from a catchment of 1172 hectares and is calibrated by current meter (Figure 1.4) It is a Leupold and Stevens 2A 35 recorder. The flume drowns at a very low level, so that control is channel control, resulting unfortunately in being insensitive to low flows with poor reliability. The maximum flood level ever recorded was that during Typhoon Brenda on 20 May 1989 at 7.670 mPD (Water Supplies Dept., 1987).

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# CHAPTER 2 FLOOD HYDROLOGY

To prevent and minimize the loss in flooding in the long run, the implementation of both structural and non-structural measures are necessary. On one hand, there should be careful landuse zoning like avoiding developments on flood prone areas while on the other hand the construction of nullahs, catchwater to divert the excess flow are inevitable. Ideally, incovenience or loss of property could be assessed economically against the cost of works designed to avoid them. Hence, in a responsible and good basin management scheme, much effort has been made to predict accurately the design flood. This refers to the flood hydrograph or peak discharge value that is finally adopted as the basis for engineering design, after giving due consideration to flood characteristics, flood frequency and flood damage potential, including economic and other related factors. In fact, flood liable regions in various parts of the world have been studied in the past and numerous empirical models, mostly western (Chow 1964, Crawford 1966, McCuen and Snyder 1986, Ponce, Shaw and Simon 1989, Donker 1992) emerge to examine flooding. These models or formulas might be summarized in two main aspects:

a) the occurrence of a flood event of different scales (flood frequency) and its maximum magnitude (peak discharge) in different sized catchments;

b) the behaviour of a flood in time and in space.

The former deals more with the climatic history and characteristics of the region while the latter needs a detailed analysis of the local terrain and land use before unit hydrographs and flood routing models can be formulated. From these parameters, the spatial extent of flood hazards of different degrees and a simulation of a certain flood event might be obtained. By juxtaposing such information and the affected land uses and weighting the total cost that would be incurred to avoid the disaster in relation to the otherwise economic loss, an acceptable (both economically and socially) design structure to combat flooding could be implemented. More importantly, the aim of developing these mathematical relations from gauged or long-record catchments may be readily used to deduce situations in other ungauged or short-record catchments with similar hydrologic characteristics. This chapter will examine how some of these important flood hydrological principles are empirically derived and evaluate their applicabililty to catchments in Hong Kong.

## 2.1 Definition of Flood Water / Overland Flow

What is flooding ? Generally and for the sake of simplicity, one will consider an abnormally large amount of rainfall with great intensity as the main cause, thereby resulting in excess of overland flow over infiltration (the Hortonian overland flow model) (Beven and Carling, 1989). This is in fact but one of the many causes of and processses leading to floods. Storm runoff should include variable excess of water from variable sources like subsurface flow, throughflow (Figure 2.1).

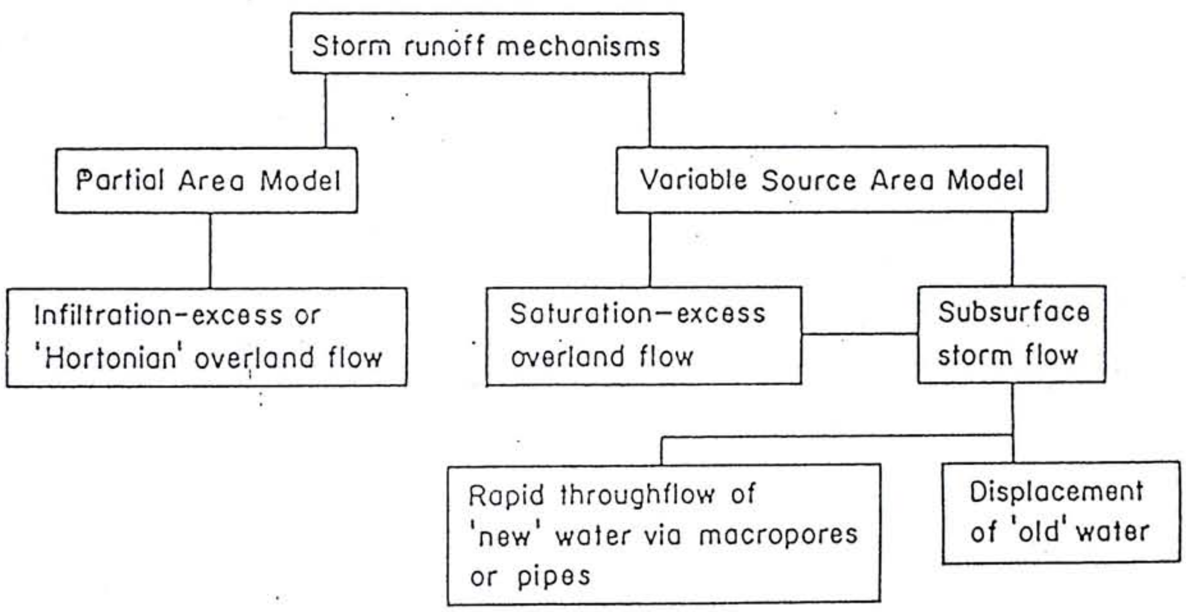


Figure 2.1 Storm runoff mechanisms.
Source : Beven & Carling (1989) Floods - Hydrological, Sedimentological and Geomorphological Implications.

Hence, to determine the volume of overland flow in a storm, one has to make accurate measurements of precipitation and calculations of storm depth, duration and intensity as well as other flow processes which might contribute to or be abstracted from the flood volume.

## 2.2 Storm Depth, Duration and Intensity

For a catchment area less than 25 km$^2$ or 10 square miles, the smallest area assumed to have negligible variation of storm depth, runoff can be modelled by assuming constant rainfall in both space and time (Ponce, 1989). Therefore, a rainfall record from 1 or perhaps 2 rain gauges in small-sized catchments can be used to analyse the point depth, defined as the storm depth associated with a given point area. In estimating the amount of flood, one has to consider a certain storm as a whole, that is from its start to the time it subsides. This lasts continuously for perhaps a few days or just a matter of a few hours with abnormally great intensity. The period of time to consider is often arbitrary and customary. Very often, the time from when excess flow of water tends to occur to when it returns to baseflow condition will be taken as the major storm period. It therefore requires accurate measurement or judgement of this break point when in real conditions, flow is actually continuous. An equation relating storm (rainfall) depth and duration is

$$h = ct^n$$

in which $h$ is storm depth (cm), $t$ is storm duration (hrs), $c$ a coefficient and $n$ an exponent (a positive real number less than 1). Typically, $n$ varies between 0.2 and 0.5, indicating the storm depth increases at a lesser rate than storm duration (Ponce, 1989). On the other hand, storm intensity and duration are inversely related. The average intensity $I$ is given by $h/t$ but a more standard form of intensity-duration model used is

$$I = a/(t+b)$$

in which $a$ and $b$ are constants to be determined by a `one-predictor-variable regression analysis' (Shaw, 1989). The latter equation takes into statistical interpretation that greater intensities are associated with shorter durations. Constants or coefficients concerning the above formulae might be derived by obtaining regional or local rainfall depth-duration and intensity-duration data for a preferably lengthy record. In addition to these models, the estimation of total storm depth has been improved by the availability of automatic and telemetred rain gauge which can record very short intervals of rain. Hence, a rainfall pattern of varying intensity of per hour or even per five-minute record can be obtained directly and needs not be averaged throughout the whole storm.

Having in mind the depth and intensity of a particular storm as calculated from gauged data or deduced from other catchments, the next step is to estimate the amount that would be lost before storm runoff would be generated as to cause flooding.

## 2.3 Infiltration

Infiltration is the process in which rain water is abstracted by seeping into the soil below the land surface. It then moves either laterally, as interflow, into streams and lakes or vertically, by percolation, into aquifers (American Society of Agricultural Engineers, 1983). By the variable source model, lateral flow might contribute to the flood volume and so the infiltrated amount should not be totally deducted for the measurement of overland flow. Infiltration is significant on only vegetative or soil surface and the process is almost negligible on cemented surface in urban areas. Thus, a change in the nature of land surface will result in quite a considerable change in certain hydrological parameters.

For a given storm, the infiltration rate tends to vary with time. The maximum rate occurs at the beginning of the storm, the initial infiltration rate, and decreases as the storm progresses in time. For storms of long duration, the rate gradually reaches a constant value, the final or equilibrium infiltration rate. Such a pattern was described in Horton's formula (1940):

$$f = f_c + (f_o - f_c)e^{-kt}$$

where $f$ = instantaneous infiltration rate; $f_o$ = initial infiltration rate; $f_c$ = final infiltration rate; $k$ = a constant and $t$ = time in hours (Figure 2.2). In

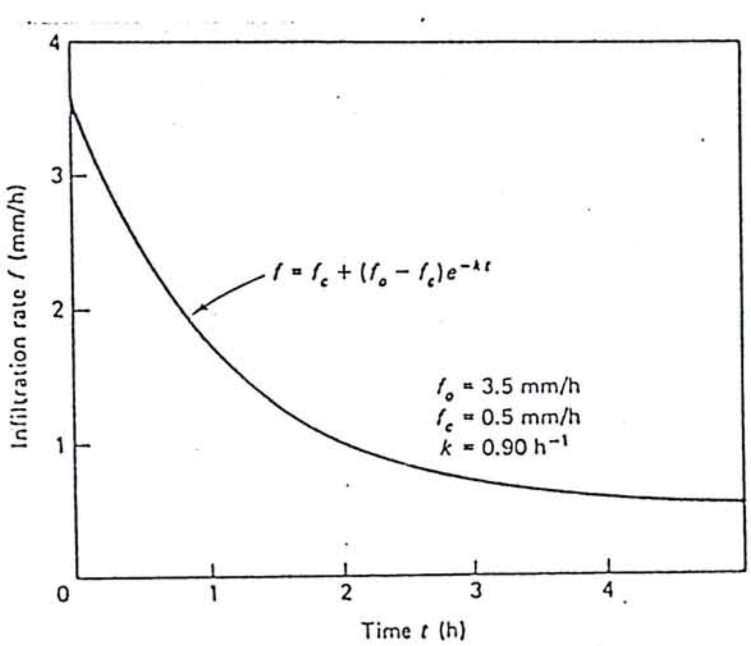


Figure 2.2 Horton's infiltration formula.
Source : Ponce (1989) Engineering Hydrology.

between $t = 0$ and $t = \infty$ , the total infiltration depth ($F$) above the $f = f_c$ line will be

$$F = (f_o - f_c) / k$$

with the units of $k$ being $h^{-1}$.

Later developments and experiments have improved the Horton's model. Philip (1960) developed a simple formula for infiltration rate related to time:

$$f = (1/2)st^{-1/2} + A$$

where $f$ = instantaneous infiltration rate; $s$ = an empirical parameter related to the rate of penetration of the wetting front; $A$ = an infiltration value that is close to the value of saturated hydraulic conductivity at the surface and $t$ = time. For $t = 0, f = \infty$ , and for $t = \infty$ , $f = A$. Integration of the formula will lead to the total depth of infiltration,

$$F = st^{1/2} + At.$$

The above two formulae require accurate and extensive field measurements to determine values of different parameters. In case such measurements are inadequate, a practical way is to model the infiltration process. This is the infiltration index ($\phi$), which assumes that the rate is constant throughout the storm (Ponce, 1989) and so is suitable for only long duration storms or catchments with high initial soil moisture content, e.g. after light summer rains, fields under irrigation. The $\phi$-index is defined as the constant infiltration rate to be subtracted from the prevailing rainfall rate in order to obtain the actual runoff volume. It thus calls for a storm pattern - a plot of rainfall intensity versus time and a measured runoff volume (Figure 2.3). Various other causes of abstractions like interception, throughflow are assumed to have been integrated into the index. But of course this method is better recommended for high intensity storms when interception is assumed to

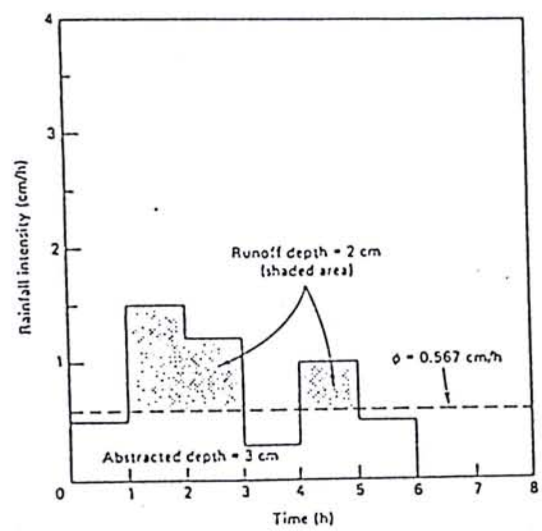


Figure 2.3 Calculation of phi-index
Source : Ponce (1989) Engineering Hydrology.

be insignificant, and for high relief catchments where surface storage is relatively small (Ponce, 1989).

## 2.4 Interception and Surface (Depression) Storage

Interception is the process by which rain water is abstracted by vegetation or other forms of surface cover. For infrequently long and heavy storms, such an amount is usually only a small portion of the total rainfall. Therefore in flood hydrology studies, the neglect of interception can be justified on practical grounds.

Surface or depression storage is the process by which water is retained in puddles, ditches and other natural or artificial depressions on the land surface. The amount is inversely related to catchment slope and estimation is based on experience. However, accurate estimations are often difficult and so it may be lumped together with interception or infiltration.

## 2.5 Peak Discharge

As early as in the 1940s, a number of formulae for calculating maximum expected flood peaks, $Q_{max}$ for individual catchments had appeared (Chow, 1964). Such peaks are assumed to be functions of one or more of the following variables: catchment area and shape, runoff volume, and coefficients and exponents to allow for special characteristics of soil, geology, drainage pattern and so forth. Among these, the Myer formula might be the simplest:

$$Q_{max} = C(A)^{1/2}$$

where $A$ is the catchment area and $C$ is a coefficient. This was called the `peak formula' which is restricted to taking only area into consideration while neglecting variations in rainfall, infiltration rate etc.. An improved method of Kuichling called the `rational formula' will be

$$Q_{max} = CAi$$

where $C$ is the coefficient of runoff and $i$ the mean intensity of gross rainfall.

The coefficient of runoff ($C$) depends on the abstractive and diffusive properties of land surface which usually ranges from 0.05 to 0.95 (Table 2.1). Its significance is to adjust according to local conditions the peak

| Description of Area | Runoff Coefficients |
|---|---|
| Business | |
| Downtown areas | 0.70 to 0.95 |
| Neighborhood areas | 0.50 to 0.70 |
| Residential | |
| Single-family areas | 0.30 to 0.50 |
| Multiple units, detached | 0.40 to 0.60 |
| Multiple units, attached | 0.60 to 0.75 |
| Residential (suburban) | 0.25 to 0.40 |
| Apartment-dwelling areas | 0.50 to 0.70 |
| Industrial | |
| Light areas | 0.50 to 0.80 |
| Heavy areas | 0.60 to 0.90 |
| Parks, cemeteries | 0.10 to 0.25 |
| Playgrounds | 0.10 to 0.25 |
| Railroad yard areas | 0.20 to 0.40 |
| Unimproved areas | 0.10 to 0.30 |

(a) Source : ASCE Manual of Engineering Practice (1960)

| Topography and Vegetation | Soil Texture | | |
|---|---|---|---|
| | Open Sandy Loam | Clay and Silt Loam | Tight Clay |
| *Woodland*[1] | | | |
| Flat | 0.10 | 0.30 | 0.40 |
| Rolling | 0.25 | 0.35 | 0.50 |
| Hilly | 0.30 | 0.50 | 0.60 |
| *Pasture* | | | |
| Flat | 0.10 | 0.30 | 0.40 |
| Rolling | 0.16 | 0.36 | 0.55 |
| Hilly | 0.22 | 0.42 | 0.60 |
| *Cultivated Land* | | | |
| Flat | 0.30 | 0.50 | 0.60 |
| Rolling | 0.40 | 0.60 | 0.70 |
| Hilly | 0.52 | 0.72 | 0.82 |

(b) Source : Schwab & et al (1971) Elementary Soil and Water Engineering.

Table 2.1 Average runoff coefficients for (a) urban areas and (b) rural areas.

Source : Ponce, V.M. (1989)

flow frequency which should not equate with rainfall frequency as implied in $i$. Logically, a higher $C$ is related to storms of longer return period (storms of greater $Q_{max}$, duration and intensity) and steeper catchments. It may also relate to total rainfall intensity and $\phi$-index in the following way :

$$C = (i - \phi) / i$$

This takes the assumptions that negligible diffusion occurs especially for steep catchments and effective rainfall intensities are constant with time. On the other hand, $C$ may vary within a given catchment if individual subcatchments are delineated and a weighted value of runoff coefficients in proportion to their areas are used.

On the other hand, the mean intensity of gross rainfall is calculated on the basis of the period of concentration ($Tc$), i.e. the time required for the most distant part of the catchment to contribute to the outflow from the catchment. Several different ways can be used to calculate $Tc$. These are based on a flow velocity (using hydraulic properties or the Manning equation) and associate a travel time through the hydraulic length. Empirical formulae have also been derived, one of which is

$$Tc = 0.0078K^{0.77}$$

where $K$ = *maximum length of travel (ft) / square root of average slope* and commonly, the main channel slope between two points is defined by excluding the 10% downstream end and the 15% upstream end along the main drainage path to the watershed boundary (Simon, 1986). This formula is applicable to small catchments where variablility of catchment shape (travel length) and slope are relatively small and data are easier to derive. Once $Tc$ is determined and for most critical floods, rain duration should be made equal to $Tc$ as proved empirically. Together with a certain storm depth or a storm in a given return period, intensity ($i$) could be obtained.

The rational formula is the most widely used method for analyzing runoff response from small catchments and urban storm drainage because it has taken into account quite a number of hydrologic processes - rainfall intensity, duration and frequency, catchment area, hydrologic abstractions, runoff concentration and diffusion. However, its inadequacies are that spatial and temporal variation of rainfall, the contribution of stormflow to runoff and antecedent moisture condition are not taken care of. Yet, these are often considered negligible in small catchments, thus making the formula still acceptable.

## 2.6 Flood Frequency

Whenever after a disastrous flood which causes loss of life and property, a common question normally will be raised: `Will such magnitude of flood happen again? When?' or `Will there be an even more disastrous one coming in the future?' Answers to these questions have to be sought in determining the design life of a structure or the design flood. With a complete and long history of climatic and specifically precipitation record, prediction will be made more reliable. However, this almost certainly cannot be realized in many flood-liable regions of the world and so estimation of return period or flood frequency is entirely based on probability computations. The probability for a storm with a given discharge ($Q$) to occur again is given as

$$P(Q) = 1 / T$$

in which $T$, the return period is defined as the time (a random variable) elapsed between successive peak flows exceeding a certain flow $Q$. A frequency then corresponds to a return period of $T$ years, or 1 in $T$ years. Nevertheless, it should be noted that the calculation is primarily based on rainfall records. Even if the same pattern of rainfall (total amount, duration, intensity) occurs in two different times, $Q$, the peak discharge may not be the same due to changing land uses (changing coefficients).

## 2.7 Unit Hydrographs

To obtain a temporal pattern of storm floods, the unit hydrograph originated by Sherman in 1914 (Ponce, 1989) is one of the simplest but common methods used. The hydrograph is produced by assuming a unit depth of runoff or effective rainfall (1 cm or 1 in) uniformly distributed over the entire catchment and lasting a specific duration. The unit increment time is normally 1 to 6 hours, suited to mid-size catchments in which rainfall duration is less than $Tc$, a subconcentrated flow. A great limitation of the unit hydrograph is its implication of linearity - constancy or uniformity in a number of variables like rainfall intensity, discharge, mean velocity etc.. Besides, it is limited to catchments with gauged rainfall and runoff records and well defined storms, ie. with no rainfall preceding or following it. Hence, unit hydrographs are not suitable for very large size catchments which might involve too many variations.

To derive a unit hydrograph, one aspect is to determine the catchment lag or basin lag ($t_l$), the time elapsed from the occurrence of unit rainfall to the occurrence of unit runoff. This lag time is often difficult to define and the most commonly used one is that from the centroid of effective rainfall to the peak of runoff (Figure 2.4). As it is very much related to catchment characteristics, a general expression is given as

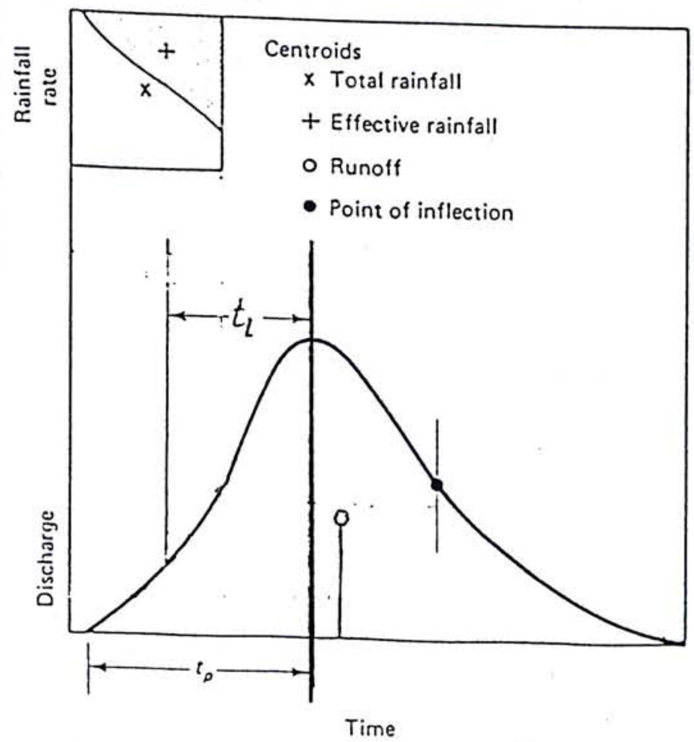


Figure 2.4 Time lag in unit hydrographs.
Source : Ponce (1989) Engineering Hydrology.

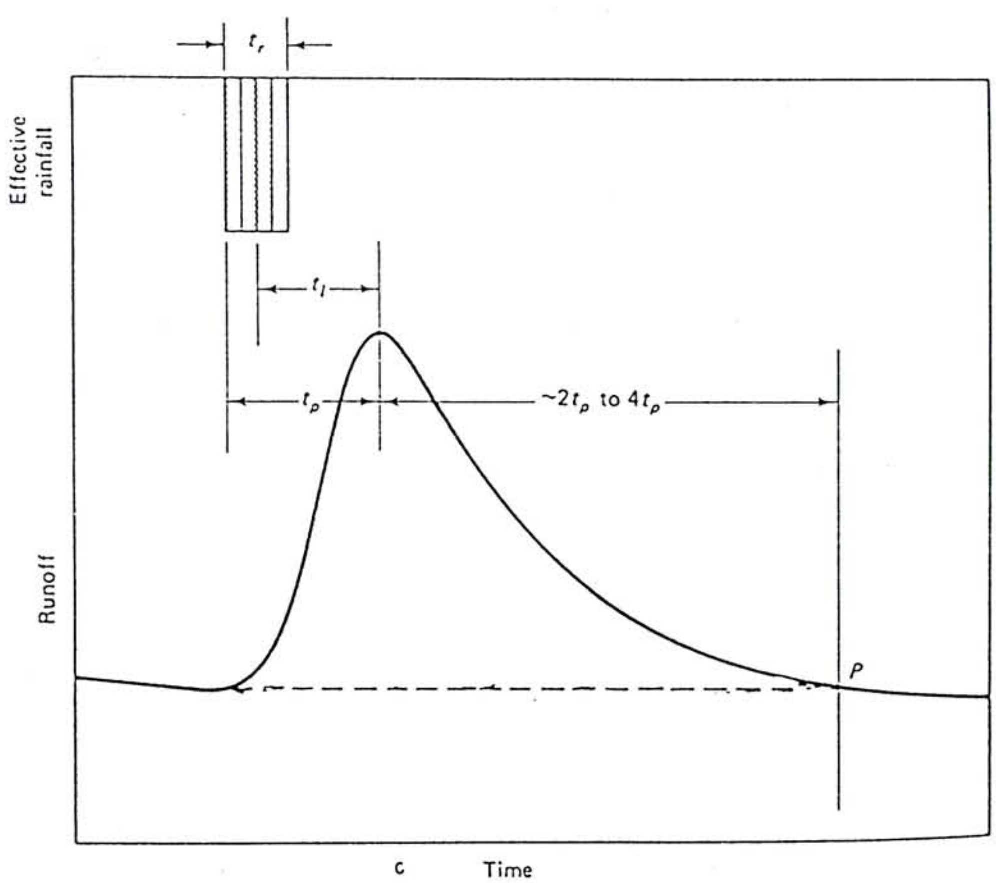


Figure 2.5 Procedures for baseflow separation.
Source : Ponce (1989) Engineering Hydrology.

$$t_l = C\ (LL_c / S^{1/2})^N$$

in which $L$ is catchment length along the main stream from outlet to divide, $L_c$ is length to catchment centroid, $S$ is a weighted measure of catchment slope and $C$ and $N$ are empirical parameters.

Another aspect is to separate the direct runoff from the baseflow (with interflow included) in the computation of the unit hydrograph. This is again arbitrary and to identify a point in the receding limb of the measured hydrograph where direct runoff ends, the normal procedure is to take the receding time up to that point about 2 to 4 times the time-to-peak (Figure 2.5) and then draws a straight line connecting the start and end of the storm (Ponce, 1989).

## 2.8 Synthetic Unit Hydrographs

In case of ungauged catchments, unit hydrographs may be derived by synthetic means from established formulae. The concept was first introduced by Snyder in 1938 (Ponce, 1989) in the analysis of catchments of the Appalachian region. Based on catchment geometry and slope and the shape of a unit hydrograph, he gave formulae concerning basin lag, peak flow, unit hydrograph duration, time to peak and actual time base -

those essential elements for the construction of a unit hydrograph. These are listed as follows:

$$\text{Basin lag } (t_l) = C_t(LL_c)^{0.3}$$

in which $C_t$ is a coefficient of catchment gradient and associated storage. It varies from 1.35 to 1.65 with a mean of 1.5.

$$\text{Peak flow } (Q_p) = 2.78 C_p A / t_l$$

in which $Q_p$ is the unit hydrograph peak flow corresponding to 1 cm of effective rainfall ($m^3$/sec) and $A$ the catchment area ($km^2$).

$$\text{Hydrograph duration } (t_r) = 2/11\ t_l$$

$$\text{Time to peak } (t_p) = 12/11\ t_l$$

$$\text{Time base } (T_b) = 72 + 3t_l$$

It should be noted that Snyder's synthetic unit hydrographs are derived empirically from mid-sized and fan-shaped catchments. So runoff response belongs to subconcentrated type, with rainfall duration about 20% less than time of concentration. Besides, coefficients $C_t$ and $C_p$ should be determined on a regional basis.

Another popular method is the SCS Synthetic Unit Hydrograph developed by V. Mockus in 1950 (Ponce, 1989). Assuming a constant ratio of triangular time base to time-to-peak (5) and a constant C (0.6875) and using a dimensionless hydrograph function to calculate time lag, a standard unit hydrograph shape is produced. These `constants' that make the method less flexible than the previous one but is easier to produce based on limited data available.

## 2.9 Catchment Routing

While unit hydrographs give a temporal pattern of storm floods, catchment routing enables a track of both temporal and spatial flow pattern. Various methods have been devised depending on the type of data available. The hydrologic catchment routing methods are based on rainfall pattern while the hydraulic methods rely more on the channel configuration. To make a more realistic approximation of flow pattern, both translation or runoff concentration and storage or runoff diffusion should be incorporated into the methods. It is universally true that more variables would make models complex and difficult to handle.

For small-sized catchments with lack of detailed information concerning channel characteristics like goemetry, friction, the Time-Area Method and the Clark Unit Hydrograph of the hydrologic catchment routing method (Ponce, 1989, Institute of Engineers, 1991) may be sufficient. These are based on the derivation of a time-area histogram, ie. a histogram of contributing catchment subareas. Subareas are zones

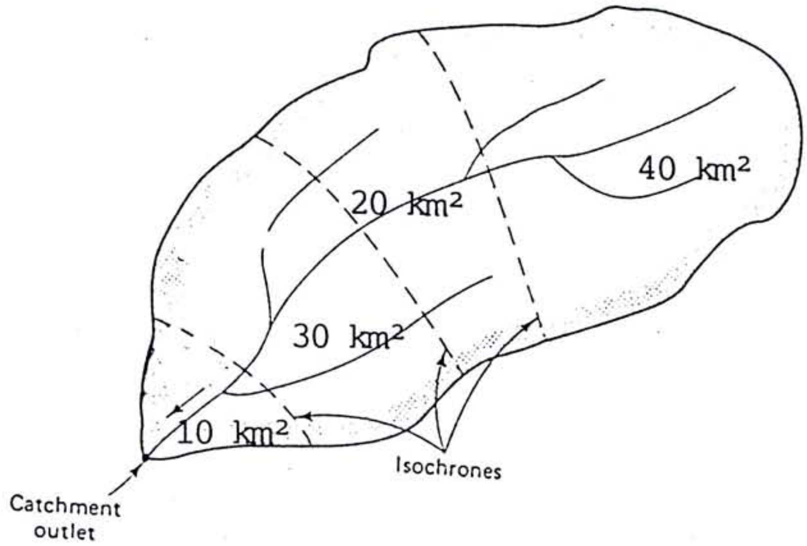


Figure 2.6 Isochrone lines of a drainage basin.

| Time (h) | 0 | | 1 | | 2 | | 3 | | 4 | | 5 | | 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Effective rainfall (cm/h) | | 0.5 | | 1.0 | | 2.0 | | 1.5 | | 1.0 | | 0.5 | |

Use the time-area method to calculate the outflow hydrograph.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| | Partial Flows and Sum (km²-cm/h) | | | | | | | |
| Time (h) | 0.5 cm/h | 1.0 cm/h | 2.0 cm/h | 1.5 cm/h | 1.0 cm/h | 0.5 cm/h | Sum | Flow (m³/s) |
| 0 | 0 | | | | | | 0 | 0.0 |
| 1 | 5 | 0 | | | | | 5 | 13.9 |
| 2 | 15 | 10 | 0 | | | | 25 | 69.4 |
| 3 | 10 | 30 | 20 | 0 | | | 60 | 166.7 |
| 4 | 20 | 20 | 60 | 15 | 0 | | 115 | 319.4 |
| 5 | 0 | 40 | 40 | 45 | 10 | 0 | 135 | 375.0 |
| 6 | | 0 | 80 | 30 | 30 | 5 | 145 | 402.8 |
| 7 | | | 0 | 60 | 20 | 15 | 95 | 263.9 |
| 8 | | | | 0 | 40 | 10 | 50 | 138.9 |
| 9 | | | | | 0 | 20 | 20 | 55.6 |
| 10 | | | | | | 0 | 0 | 0.0 |
| Total | | | | | | | 650 | |

Table 2.2 Time-area method of catchment routing using areas in Figure 2.6 and a rainfall record.

delimited by isochrone lines within a catchment.These lines are the loci of points of equal travel time for a parcel of water to the catchment outlet (Figure 2.6). Several assumptions are made to derive these lines and histogram. First, the time interval of effective rainfall hyetograph is equal to the time interval of the time-area histogram. Second, partial flow at the end of each time interval is equal to the product of effective rainfall times contributing subarea. Third, the lagging and summation of partial flows result in a runoff hydrograph (see Table 2.2 as an example). Finally, the time of concentration is taken as the difference between the time base of the hydrograph and the effective rainfall duration. In fact, the Clark Unit Hydrograph takes all the same principles except that a unit effective rainfall is used to arrive at a unit runoff depth and so a unit hydrograph. In both cases, since only effective rainfall data is used, it assumes only translation and will lead to higher peak flows than other methods. To remedy such an inadequacy, a storage constant (for the inclusion of diffusion effect) is incorporated into the model, which can be determined by regional analysis based on catchment characteristics. The method has been applied in many parts of the world like Lena Gulch watershed on the west side of Denver, Colorado (Johnson, 1989) and in New South Wales, Australia (Institute of Engineers, 1991). Results from several runoff events show that relatively accurate shape of unit hydrographs could be obtained.

## 2.10 Flood Hydrology in Hong Kong

In western studies which are mostly temperate regions, small catchments normally imply quite uniform local terrain and rainfall characteristics, resulting in acceptable application of simplified parameters or variables in determining flooding. In Hong Kong, although catchments are small, the rugged relief, varying landuses within a small area and large variations of floods from year to year make predictions not such a straightforward and simplified task. This is because under tropical climates, variation in rainfall amount and intensity are much greater over small areas and with time than those in temperate areas. Also, rain intensities are much greater. A rather comprehensive study on design flood was made only in 1968 (P.W.D., 1968) from extremely short of rain and stream gauge records at that time (most were less than 10 years). Hence, results were based mostly on western-derived models or formulae. Nevertheless, it did give a preliminary quantitative look at flooding for later more large scale studies and management scheme in Hong Kong, notably by the Drainage Services Department in the early nineties.

Peak discharge was calculated by various methods - rational formula with different constants used, straight envelope, curved envelope, Creager's curve (Chow, 1964) - but none seemed reliable because of inadequacies in rain gauge data. Only stations with the longest records were used to approximate the flood frequency distribution of the whole territory. Even then, these data had to be combined together, though from catchments of very different characteristics, to make a total of merely 16 years!

On the other hand, the hydrometeorological method (including the unit hydrograph, synthetic and dimensionless unit hydrographs) yield more satisfactory results and is more practical to Hong Kong as a long data record is not required (P.W.D., 1968). As storm duration was normally short and catchment size was very small, a 15-minute unit time was adopted instead of on hourly basis and point rainfalls were used. Besides, hydrograph separation was made only from baseflow but without any interflow. Net storm rainfall was computed by the k-index method and although loss rates varied largely from place to place, for safety purpose, a low rate of 0.12 in/h. was assumed for the design of major structures in Hong Kong. Finally in ungauged catchments, synthetic and dimensionless unit hydrographs were used. Figure 2.7

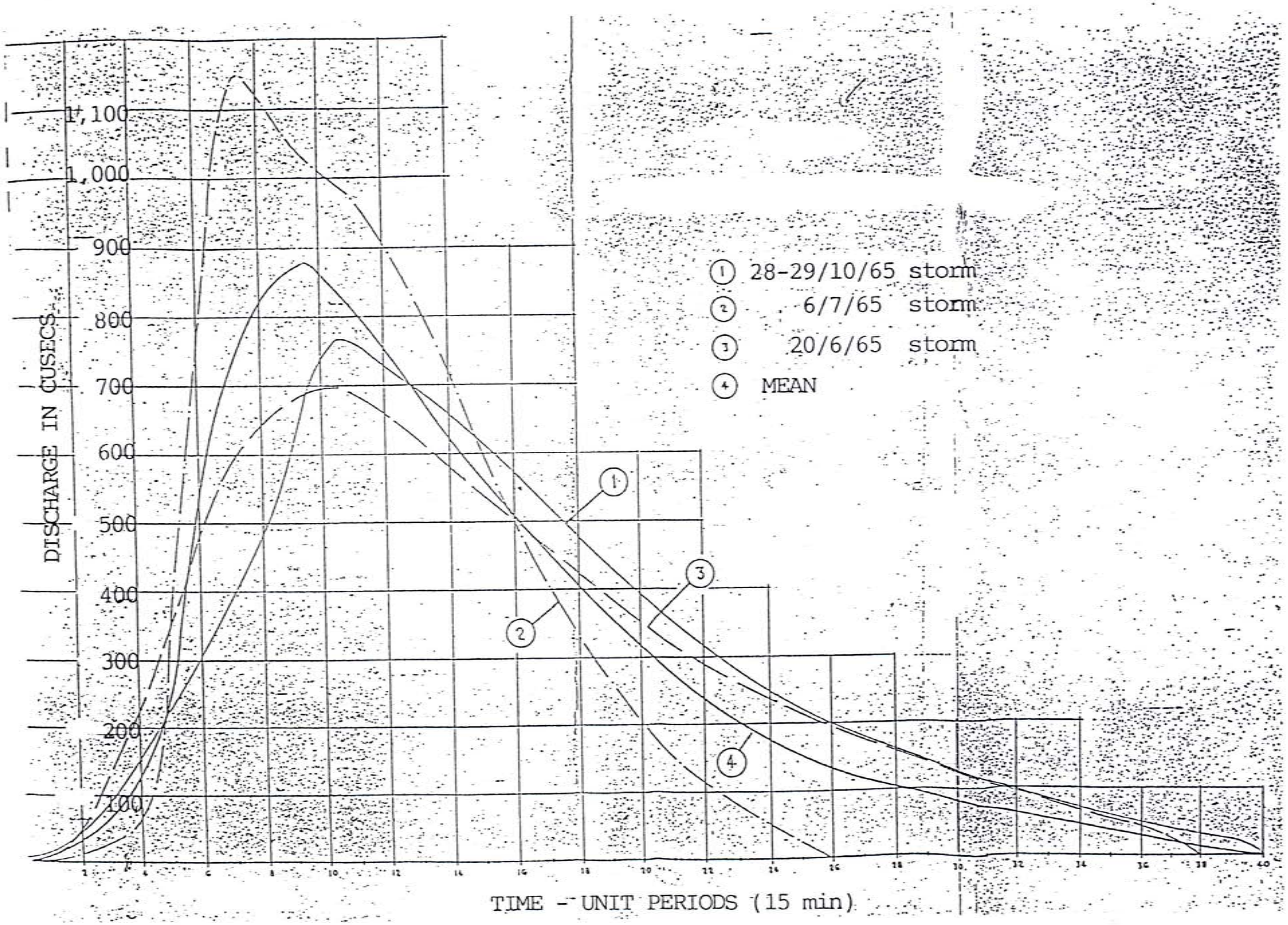


Figure 2.7 Unit hydrographs of selected storms produced from Kam Tin Gauge.
Source : P.W.D. (1968) Design Flood for Hong Kong.

shows some of the parameters derived for Kam Tin catchment area at that time. Though it had been concluded that the hydrograph methods were a little more successful in reaching the desired results, and though we have the most dense network of rain and stream gauges in Asia, difficulties were still encountered due to instrument faults, mislocation and time errors in chart setting. It had been admitted that more accurate results had to wait until more data and better technology become available in the future.

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# CHAPTER 3 APPLICATION OF GIS IN HYDROLOGICAL MODELLING

## 3.1 Traditional Hydrological Studies

The behaviour of water in the hydrological cycle is complex, attributed to numerous processes and variable environments in the atmosphere, biosphere and lithosphere. Scientists have been trying to disintegrate these intricate relationships or framework into simpler parts, entailing each for deeper studies. Hence, climatologists might be more interested in atmospheric circulation and precipitation relationship, biologists in precipitation-plant interception relationship while land managers and engineers will concentrate on river hydraulics, groundwater movement and the like. One should also not ignore the environmentalists, educationalists, geographers and scholars in many other disciplines who are in one way or the other interested in the study of water.

For at least 150 years or so, much emphasis had been placed on simulating the complex hydrological processes with different models, some of which have been discussed in Chapter 2. This very often was studied in a controlled or micro-scale environment. In other words, owing to limited resources and capability in collecting data from wider areas, investigation would be carried out in laboratory models or in a prototype area which may be a certain stream stretch, a small woodland, a pipe etc. of small areal extent. Such experimental results were then used to extrapolate to other areas of similar characteristics. Ever since the mid 1960s when computer models began to appear, there are literally hundreds of public domain computer programs for hydrologic modelling (Maidment, 1993), and these are largely concerned with surface and subsurface water.

## 3.2 Geographic Information System and Hydrologic Modelling

With the advancement of computer technology and collection and integration of varying spatial information, it has been able to increase the degree of definition of spatial subunits in hydrologic studies, in terms of number and descriptive detail, from local to regional or continental-scale (Maidment, 1993). The potentials of GIS lie not only in its ability to handle voluminous data, especially in hydrologic parameters that go into modelling like terrain, land cover and soil, but also in data query and analysis, and displaying information with predetermined symbology (Harris et al., 1993). This might be exemplified by numerous studies that have been going on in the past few decades.

Hydrologic/hydraulic studies would normally require a wide range of information - temperature, pressure and wind pattern in the atmospheric system to determine evaporation and precipitation characteristics; the type of vegetation cover to determine interception and evapotranspiration; soil and land use type to determine infiltration; slope, aspect and stream channel configuration to determine the behaviour of both surface and subsurface flow. Besides, in interpreting how man's activities might alter these processes, information on dams and reservoirs, drainage and irrigation systems are also needed. There could be a lot more in the list. Although past studies try to isolate each of these processes as mentioned in Section 3.1, their interdependence in time and space are of vital importance to model accuracy. Hence, the geographic information system not only increases the studied area extent, but also brings these relationships altogether.

In applying such models with GIS, the normal procedure is first to identify a 2-dimensional spatial pattern of input information which are collected by various means as points, lines or areas. These may be discrete data such as the occurrences of wells, streams and spots of showers, or continuous data by nature such as elevation, pressure. The latter would usually be interpolated and built into a 3-dimensional continuous surface. In addition, as hydrologic processes are very dynamic in nature, a 4th dimension of time has to be incorporated into the model. Eventually, the result is to arrive at a spatial and temporal pattern of the intangible processes of evaporation, precipitation, surface flow and so on.

Nevertheless, no matter how successfully developed the mathematical hydrologic models are by non-GIS means, almost all researchers, when applying them in a spatial context, face the fundamental problem of data shortage or inconsistency and have to seek out alternatives. In modelling the effects of climatic change on the Gunnison River Basin in Colorado (Hay et al., 1993), subcatchments are first characterized by numerous topographic and geographic variables like slope, soil type, vegetation type. From these parameters, processes affecting water budget such as potential evapotranspiration is then modelled with daily values of air temperature, precipitation and solar radiation. However since precipitation data are sparse but important in mountainous basins, these are supplemented by a precipitation model requiring upper-air measurements and gridded elevation data. In this aspect, the orographic precipitation model could be linked with GIS as it automates the development of elevation grids from DEM point elevation values, making it possible to assess the effects of topographic scale on precipitation estimates (Hay et al., 1993). Finally, effects of climatic change could be simulated by nesting general circulation and watershed models together. With the verification of satellite and streamflow data, uncertainty in the model can be decreased to an average of less than 10% and actual volumes obtained using precipitation model estimates are comparable to those produced using observed data.

In another study of modelling surface flow (Donker, 1992), the basic parameters needed are the creation of an elevation matrix with GIS. The cells of the matrix are then ranked from highest to lowest elevation for the purpose of defining flow direction with the maximum slope. A flow accumulation function or a weight matrix is also added to each cell. This sums up the weights of all elements in the matrix which drain to that element and so a drainage network and the delineation of its basin is defined. From these other important hydrologic parameters in catchment routing like maximum flow length, time of concentration, area can be derived easily. With reliable rainfall records available, this provides a basic model for runoff routing. In fact, similar approaches have also been documented in other studies but with different objectives. Some concentrate on the effects of flooding (Bitters et al., 1991; Brimicombe &

Bartlett, 1993; Hoggan, 1989; Williams et al., 1991), thus requiring data on channel characteristics and flood diversion structures as well to simulate storm flow with time. Others may like to derive a distributed rainfall-runoff model (Gao et al., 1993) or to analyse the hydraulics of surface water flow (Richards et al., 1993). In whatever cases, the cells of the matrix would have to be assigned different attributes or variables which accelerate or retard the flow rate from one to another.

Hydrologic modelling, on the other hand, can also be linked up with socio-economic activities. Concentration of various pollutants as driven by water flow can be assessed for environmental planning (Institute for Hemispheric Studies, 1994). In the agricultural regions of the Methow Valley, water budget is calculated with crop types and groundwater flow conditions, thus assessing the need for irrigation (Heminway & Harper, 1994). Besides, historical and well-documented records of past topography and hydrology can facilitate the construction of a record of landscape change that is convertible into GIS coverages. These are then superimposed on more current information, so that probable inappropriate and maladaptive land use in the past, present and future can be assessed. And this is studied for the surface hydrology and the accumulation of hazardous materials on American bottoms from 1890 to 1980 (Samsel & Colten, 1988). Finally, in the study of prioritization of drainage system repairs in Charlotte (Cash, 1994), socio-economic and cultural information of open land ratio, complaints ratio, road overtoppings, etc. for each basin are overlaid, compared and analysed. Therefore, with the capabilities of GIS, greater discovery and more subtle, intricate or intangible relationships could now be unveiled by means of new perspective of visualizing the behaviour of running water together with its associated physical and/or cultural systems. Given the time and manpower constraints, GIS is really able to reconstruct the reality from scattered, may be piecemeal, sources of information.

In summarizing the different aspects of hydrologic study with GIS, undoubtedly terrain, amongst all, is the most important parameter. However, data collection and manipulation in the form required (ie. slope, contour, aspect etc) could be the most tedious if performed in the field. This could take up much more time than the derivation and application of the mathematical model itself. Past studies therefore have to confine the physical setting to a manageable extent. With the built-in functionalities of digital elevation modelling in most GIS software, terrain information from varying sources - maps, remotely-sensed data, could be captured, integrated and interpolated. Derived parameters like slopes, aspects, contours as one wishes can readily be used as input to hydrologic models. In analysing groundwater flow of San Gabriel Basin (Harris et al., 1993), contoured or point data are used to generate continuous surfaces from which nodal values of pumping wells above the aquifers can be defined. But as commented by the authors themselves, the interpolation routine of GIS may generate a surface that deviates substantially from the data in areas with few data points. Similarly, MAPHYD - the hydrologic modelling system used in Lena Gulch watershed, Colorado (Johnson, 1989) requires the input of elevation and upslope distance data in digitized topographic base maps to derive slope parameters, aspects, runoff directions and distances. Even in Hong Kong, contours from 1:5000 scale topographic maps are important to hydraulic modelling of the lowland area, deriving flow direction and topographic break of slope (Brimicombe & Bartlett, 1993). In fact, terrain modelling has become the most frequent, and in some the only, aspect of GIS execution linking to a wide range of hydrologic studies.

Automated interpolation techniques could also enable the creation of trend surfaces of continuous phenomena. In South Canterbury of New Zealand, telemetred readings from 12 rain gauging sites are used to produce a modelled isohyet map (Williams et al., 1991). The package also produces mean and total rainfall estimates for all or selected catchments. In the north coast of Puerto Rico, pollution trend surfaces in surface water bodies (streams and lagoons) were extrapolated from sampling stations and results were averaged from a 10-year period (Institute for Hemispheric Studies, 1994). In many studies, water level as derived by hydrologic/hydraulic mathematical models for numerous stations are then interpolated to form a flood hazard map. Such information are useful, for instances, to support the US Flood Insurance Program (Cotter & Lohmann, 1993), to aid decision-making in Basin Management Plan of Hong Kong (Brimicombe & Bartlett, 1993) or to advise on military activity along river banks of the Han River, South Korea (Bitters et al., 1991).

It is true that by terrain modelling capabilities, the study unit can now be extended to a watershed, a basin or a catchment and need not be treated as 'lumped' sytems, meaning a zero dimensional representation of spatial features (Maidment, 1993). However, accuracy to which the model can represent the real landscape depends very much on the density and distribution of data input. As most digital information comes from topographic maps which are actually secondary type of information source, scale, numbers of survey points and the method of contouring all have influences on the configuration of digital terrain model. Besides, manual digitization of these map sheets can be tedious. In flood hazard mapping carried out by the US Federal Emergency Management Agency (Cotter & Lohmann, 1993), correction of digitized data can be up to 30% of the entire digital data set per map. The amount of time required for quality control and editing is two and four times of that of simply digitizing data. In fact, the error level varies, depending on the operators'experience and the complexity of the original geometry digitized. On the other hand, with the development of raster processing techniques in recent decades, the size of unit grid cell or pixel determines the scale at which details start to appear, and this in turn depends on the resolution of data source. Certainly, it is also governed by the scope of area concerned and the amount of generalization required. So unit cells ranging from 10 $km^2$ grids for the Gunnison River Basin, Colorado (Hay, et al 1993) to 100 $m^2$ (Donker, 1992) and even to just 10 $m^2$ in small catchments of Hong Kong (Brimicombe & Bartlett, 1993) could all be found.

## 3.3 Problems and Limitations

Hydrologic phenomena vary in all three space dimensions, in time, and are random or uncertain because they are driven by the relative randomness of rainfall occurrence and because many of the properties of flow domain are unknown (Maidment, 1993). Hence, hydrologic models and more so for hydraulic models are characterized by complex mathematical representations. These so far are left to the jobs of hydrologists, engineers and geomorphologists by non-GIS means (Brimicombe, 1992). The main role of GIS still acts as a digital cartographic tool, storing and manipulating data for model support. None of the popular software used today - Arc/Info, Intergraph, Genasys or Grass possess tools specifically for hydrologic or hydraulic mathematical modelling. This may also be because surface or subsurface flow is by its nature very dynamic and varies with time, attributed by non-spatial factors. increasing number of unknown variables. Hence, in the study of San Gabriel Basin, the GIS and the CFEST Model are both left apart, with all their capabilities left intact, but tied together with a network of programs that communicate between them (Harris et al., 1993). It has been found to work well enough than to reconstruct the architecture of the model to make it compatible with a GIS environment. In the same way, in modelling climatic change of Gunnison River Basin, Colorado, true interfaces between process models and GIS is found very programming intensive and is deemed beyond the scope of work for the study (Hay, et al , 1993). In another study of linking GIS to a distributed rainfall-runoff model, several idealized two-dimensional hydrological processes and their interactions are used to simulate a complex three-dimensional natural hydrological phenomenon. In doing so, adjusting the unknown or uncertain parameters to calibrate the model is found extremely tedious (Gao et al., 1993).

It is true that GIS enables modelling of surface/subsurface flow of a wider area, allowing analysis of spatial variability owing to heterogeneous environmental conditions. Yet, parameters required for modelling are so numerous and spatially variable that one often finds it even more difficult to collect or derive than the models themselves. Model accuracy is obviously limited by the requirement for large amount of data of good quality (Gao et al., 1993). In the Han River study of South Korea, the availability and well-documentation of extensive basic stream flow data from 16 gauges over the entire length of the river has resulted in accurate modelling and reasonable prediction of flooding effect (Bitters et al., 1991). But in many applications, owing to insufficient or unavailable data source, some parameters that serve as input to the models have to be lumped or generalized. This is especially true for the intangible hydrologic processes of which data are often difficult to obtain from wide areas. Using phi-index and SCS runoff curve number (CN) as infiltration values for rainfall-runoff modelling in Colorado (Johnson, 1989) and in Hong Kong (Brimicombe, 1993) are good examples. On the other hand, as hydrologic studies often extend to vast remote and inaccessible areas, verification of the models or results by ground observations are often impossible and so neglected. Even this may be done by remotely-sensed data of aerial photographs or satellite imagery, the very dynamic and micro-scale change of water behaviour would make such verification difficult.

## 3.4 Future Trends of Development

As hydrologic modelling requires a combination of numerous parameters, much efforts have been placed on speeding up data capture and processing while maintaining a high degree of accuracy. Developments in raster processing techniques have produced elevation model in form of matrix or cells, aiding stream ordering and flow direction determination (Donker, 1993). Many of the foregoing examples have found raster forms of input and processing successful. Recent studies have shown that raster form of data input and manipulation have been receiving greater attention due to its increasing resolution and processing speed. Besides, more data from remotely-sensed photos or imagery which are in raster forms can be available for use in hydrologic modelling. These primary information sources, by comparing with maps, cover wider areas, easier and faster to collect and input to hydrologic models. All those developments would aim at maintaining the merits of being time- and cost-effective in using GIS.

Recent developments in GIS have been towards the space-time domain and 3D analysis and representation. This would merit hydrologic studies as flows are time varying and the motion of water is truly a 3D phenomenon (Maidment, 1993). More accurate simulation is now possible when compared with models of mere two-dimensional steady-state flow and transport in the horizontal plane for most past studies. Lastly, complex mathematical relationships in hydrologic/hydraulic models may now be designed and incorporated in expert systems which are then linked to spatial-relational data models of GIS, in the hope that these packages can be used by hydrologists and engineers without the need for intervention by GIS staff.

□

# CHAPTER 4 METHODOLOGY

In previous chapters, some methods of hydrological studies to drainage basins in Hong Kong have been examined. Most of which can just reach rough estimates of flood parameters and lack a detailed analysis of both spatial and temporal variations. Accurate forecasting methods or measurements are not undiscovered but require extensive information on local terrain and hydrological data. Besides, calculations could be voluminous and complicated if performed manually or with just computers of limited memory power. With the advent of computer and information technology, simulation of flood events becomes more popular and realistic. In Hong Kong, large-scale implementation of digital environmental information has only been started recently and is still undergoing constant review. The methodology discussed below has to take into consideration on one hand, some well-known hydrology theories and procedures practised in other basins of the world; and on the other hand, the local terrain condition and available data and information system in Hong Kong.

## 4.1 The Conceptual Framework

To derive a spatial and temporal pattern of overland flow from the storm periods as mentioned in Chapter 1, Clark's unit hydrograph method which parallels the time-area approach is adopted. First, time of concentration is calculated for each stream in the studied upland catchment from its source to the outlet at 40 metre high based on the Kirpich formula. From these, isochrones (ie. lines of equal concentration time) of 5-minute interval could be interpolated. Next, areas bounded in between consecutive isochrones or with the watershed will be used to obtain the total amount of overland flow for that subregion for specific time intervals. This is achieved by multiplying area with each 5-minute rainfall record, so that the resulting storm depths will vary both spatially and temporally. However, before such multiplication takes place, each rainfall record should be deducted by a constant of 0.25 mm. This is the only phi-index empirically derived by the Water Services Department during 1965 for 43 storms in 8 natural catchments (G.C.O., 1984). It had been established that there is a limiting phi-index of about 3 mm per hour for long duration storms (Figure 4.1), ie. 0.25 mm per 5 minute. This index indicates the amount of rainfall falling on a catchment area above which further rainfall would appear as runoff (G.C.O., 1984), thus averaging the total amount of abstraction throughout a storm. Finally, summation of all partial flows for every 5-minute time lag produces an outflow hydrograph as exemplified in Chapter 2.

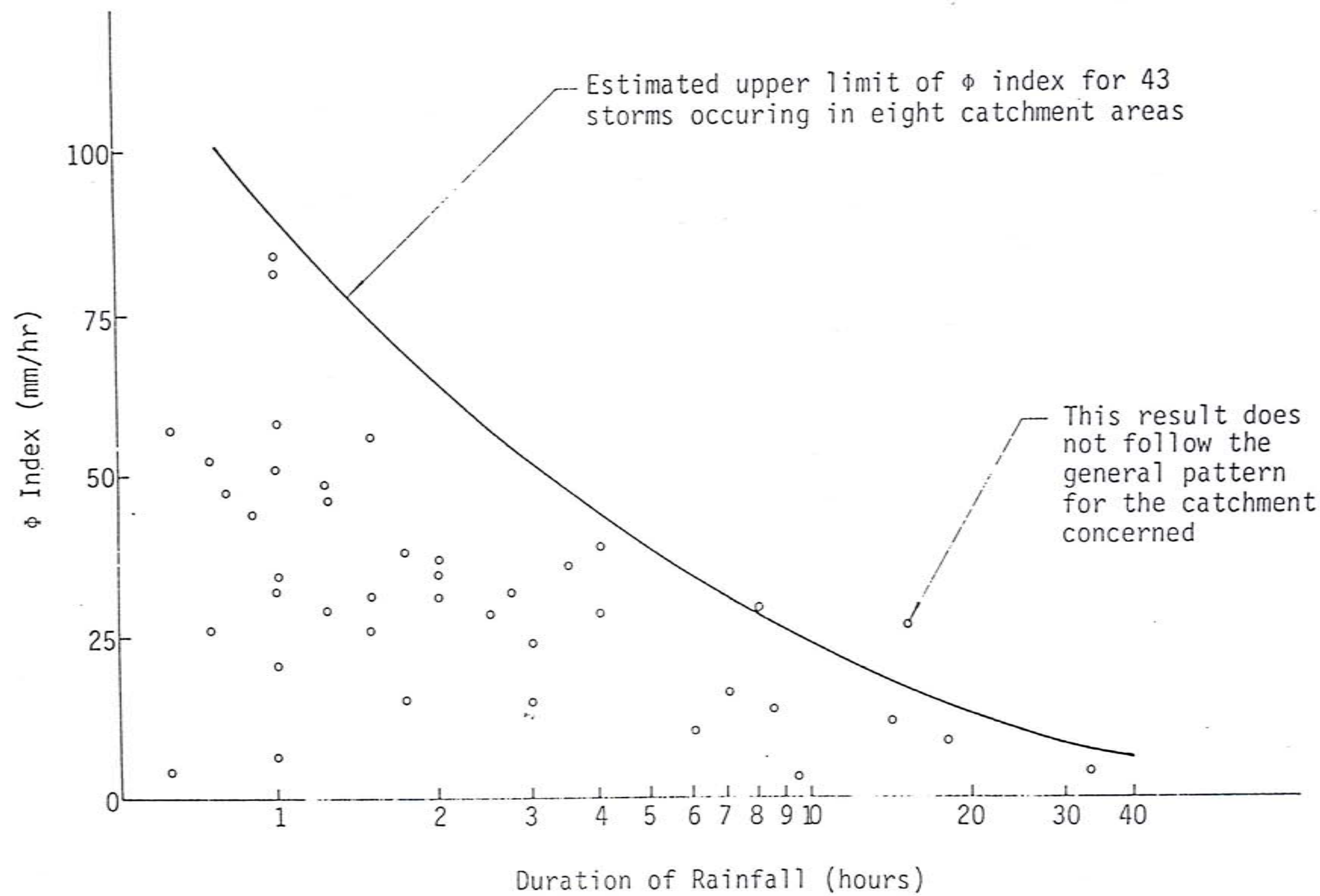



Figure 4.1 Phi-index for Hong Kong catchments. Source : G.C.O. (1984) Geotechnical Manual for Slopes.

The time-area method is essentially an extension of the rational method. But it also takes into account the temporal variation of rainfall intensity and does not rely on runoff coefficients. Nevertheless, the relative ease of using this method has incorporated several assumptions, notwithstanding the complexity of real situation:

a) point depth from one rain gauge record is assumed to be applicable for the whole area concerned;

b) loss through interception, infiltration, surface storage and so on are lumped into a phi-index by which abstraction value may of course be underestimated at the beginning of a storm while overestimation will occur at the end;

c) area, as in the rational method, is a significant variable contributing to the spatially varying amount of overland flow;

d) storm duration is made equal to the time of concentration as reflected in the hydrographs derived.

The advantages of the method lie in its simplicity, applicability to small and mid-sized catchments and requirement of mere hydrological and meteorological information which are more easily available. The next few sections will concentrate on the data source and requirement, their accuracy and reliability and how these are built up using the geographic information system for modelling.

## 4.2 Data Source and Quality

### 4.2.1 Terrain Data

To obtain a detail and complete correct record of local terrain is nearly impossible. Slight deviations from the actual landscape may, however, be acceptable as long as critical points of elevations like summits, depressions are not neglected. In Hong Kong, survey data are extensive and updated frequently especially in urban lowlands as reflected in the 1:1000 published map sheets which can achieve an accuracy of 1 metre. On upland areas of higher than about 100 metres, survey points are more scattered but critical points of mountain peaks, gaps, rock outcrops are still available on these map sheets. Besides, contours of 2 metres interval are interpolated from photogrammetric plot of aerial photographs. Although map revision is not as constant as those of the lowland regions, the assumption that less man-induced changes in this relatively remote part of the landscape still finds such terrain information quite accurate and adequate.

Hence, the basic data source for GIS input consists of 1:1000 map sheets from the Survey and Mapping Office of the Buildings and Lands Department. In areas where maps of such scale are not available, it is supplemented by 1:5000 map sheets (Appendix A). As these are derived from 1:1000 maps using photomechanical process of reduction, information of the 1:5000 maps are no less than their larger-scale counterparts except that digitizing accuracy of map information may be affected.

With all these available terrain information shown in form of spot heights or contours, primary data like elevation and derived ones like slope, aspect, surfacelength (Section 4.5) could be used in runoff modelling.

Catchment and subcatchment boundaries are digitized from a 1:20000 map supplied by the Drainage Services Department. Intersection of the major watershed and the 40 metre contour actually defines the upland catchment area concerned which is part of drainage basin no. 9 of the territory (Figure 4.2). Though data input may not be precise at this scale, this will later be edited or adjusted to a more accurate location when detail stream data are available.

### 4.2.2 Stream Data

In hydraulic methods, the geometry and configuration of a stream like channel width, length, roughness of channel bed are important input

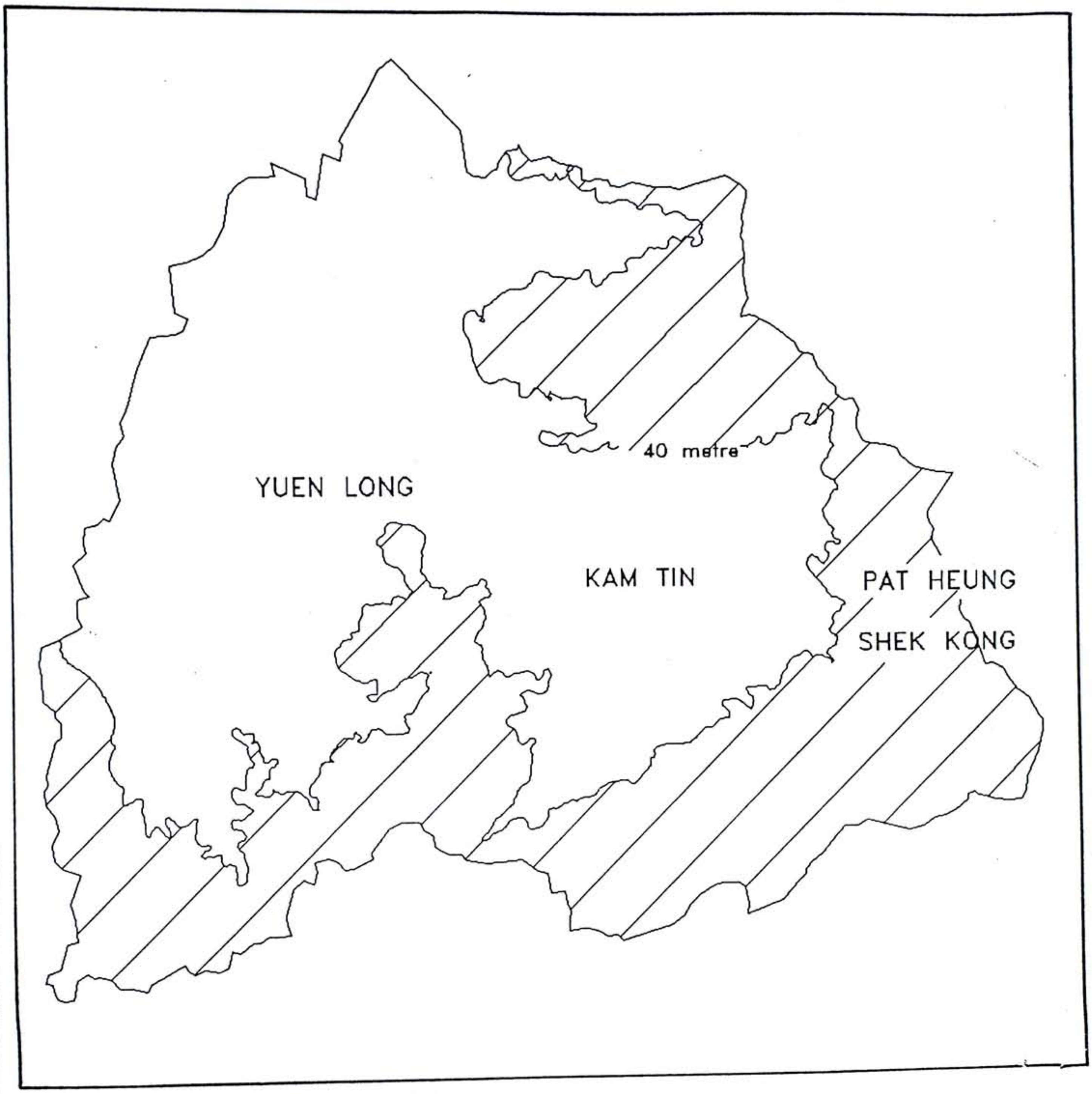



Figure 4.2 The study area (shaded between 40-metre contour and the watershed).

parameters. However, such detailed information seems impossible to acquire even on the largest available scale of 1:1000 maps unless field measurements do take place. In view of this, hydrology method is used in that mainly meteorological data are considered and less ground data are needed. As such, only stream surface length, slope and flow direction (Section 4.5) are essential and these can readily be obtained either directly from again 1:1000 map sheets or from the terrain information discussed above. The source height and location of each streamlet may be arbitrarily determined as usually no spot height or intersection with a contour line at the end of the linear feature will be found but for a map with 2m. interval, an accuracy of the order of 0.5m. can still be achieved. Bearing in mind that stream length may vary with seasons and years, a range of values for various parameters have to be considered.

On the other hand, only streams above 40 metres are relevant in this study. In the studied region, the 40-metre contour approximates a sharp change of slope from upland to lowland and a line of culvert sources to collect upstream flow. Between 40 and 100 metres may be defined as region of marginal land where human activities start to encroach upon (Figure 4.3). It is thus interesting to investigate into how rapidly

Figure 4.3 Areas of intensive human activity (indicated in red).

changing land uses here might affect the volume and pattern of storm runoff.

## 4.3 Processing Spatial Data Using Geographic Information System

Before going into details of how hydrological modelling is performed, some preliminary understandings of GIS operation and related data files are necessary. Features on maps, photos or other sources are input as either point, line or polygon features, each with its distinctive characteristics or attributes described in an associated data file. In

Arc/Info, these are known as point (pat), arc (aat) and polygon (pat) attribute tables respectively. Primary information generated by GIS for point features includes the point labels and corresponding location in user-specified coordinate system. For line features, coordinate locations for starting and ending points or nodes and length of the line are normally generated. Perimeter, area and adjacent polygon information are basic polygon features.

These are just a few basic variables associated with each attribute file. In fact, more parameters could be added to or calculated for features in these files. Besides, various forms of overlays or spatial analyses are possible by different combinations of parameters. Such complex interplay of spatial data has therefore manifested the powerful capabilities of a geographic information system and is distinctive in this study (Figure 4.4). The following sections will explain in greater details how these different data files related to terrain and streams are processed.

## 4.4 Building a Topographic Data Base

From the 1:1000 and/or 1:5000 maps, spot heights and intersections between contour lines and streams are digitized and built as point coverages. Digitizing coordinates of each map or coverage is converted

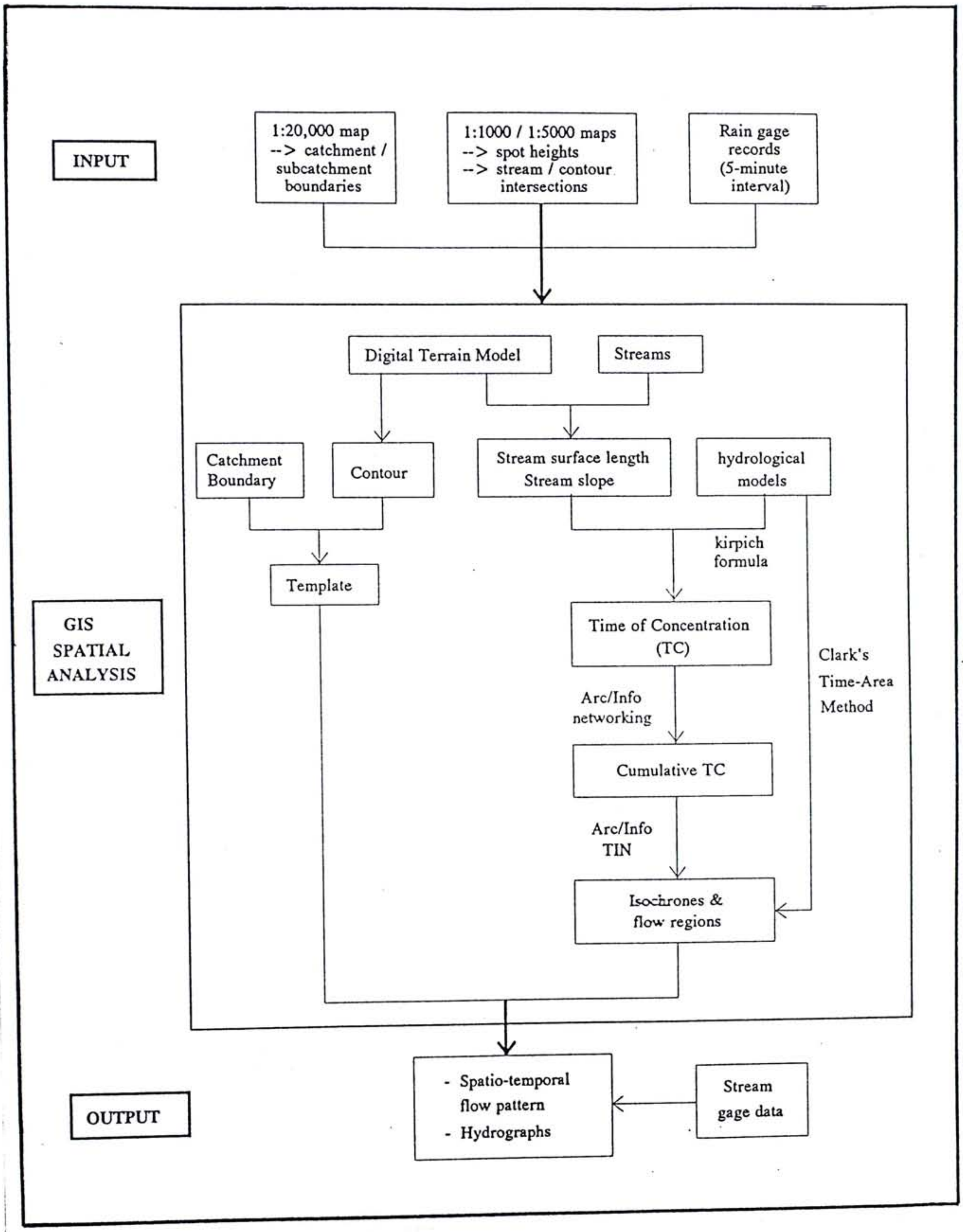



Figure 4.4 Flow chart showing GIS operations of the study model.

to Hong Kong metric grid coordinates using the registered points known as tics found at the four corners of the map sheet. This is the least square

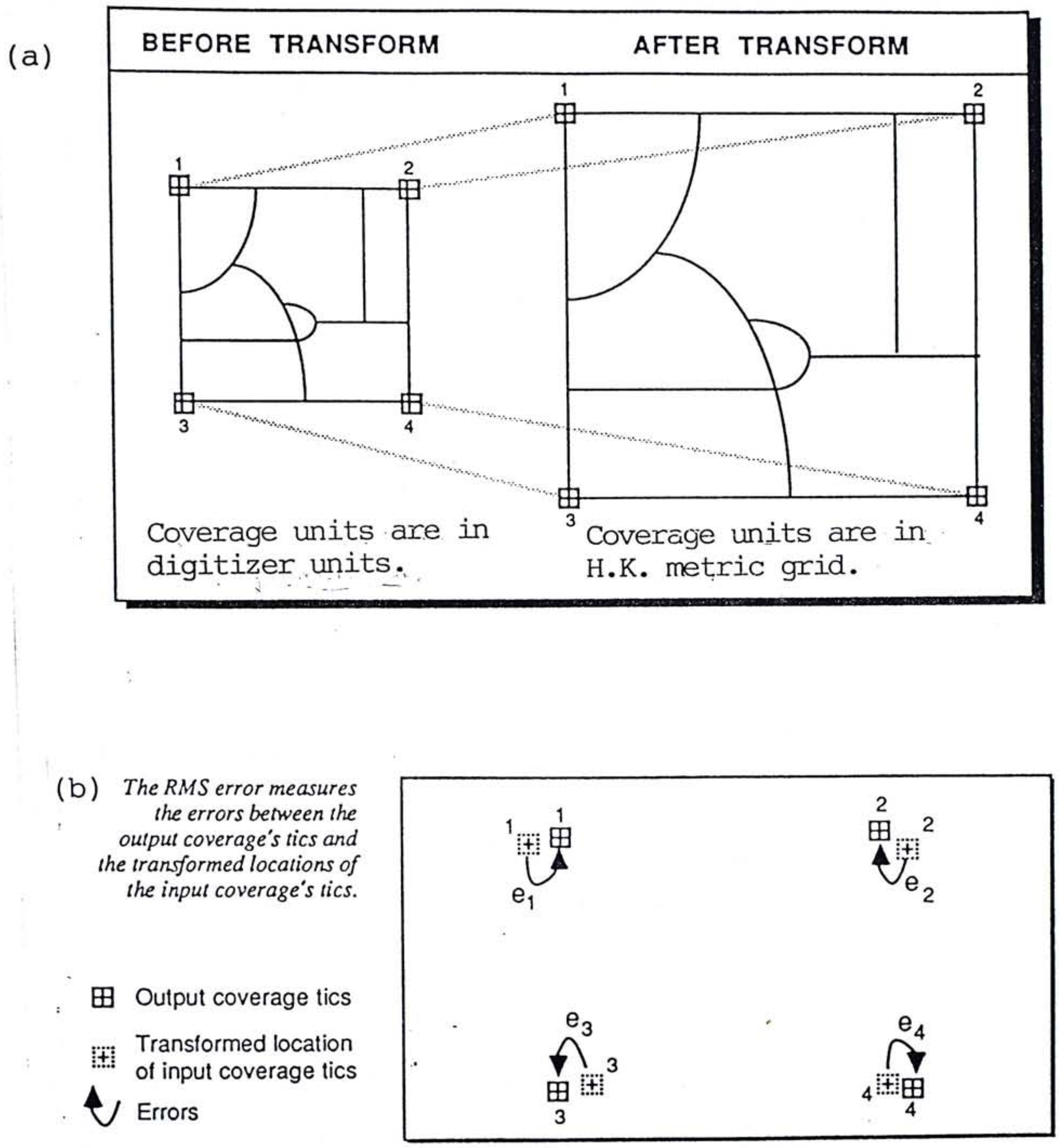



Figure 4.5 (a) The least square affine transformation and (b) the resulting RMS error.
Source : ESRI (1990).

affine transformation (Figure 4.5a) in which

$$x' = Ax + By + C$$

$$y' = Dx + Ey + F$$

where $x$ and $y$ are input coordinates of the digitizer, and $x'$ and $y'$ are Hong Kong 1980 grid coordinates after transformation. $A,B,C,D,$ $E$ and $F$ are determined by comparing the location of tics before and after transformation. A Root Mean Square (*RMS*) error is calculated for each transformation performed and indicates how good it is derived (Figure 4.5b), thus giving

$$RMS\ error = \sqrt{\Sigma ei^2} / n$$

RMS error which are kept less than 0.5 are considered satisfactory.

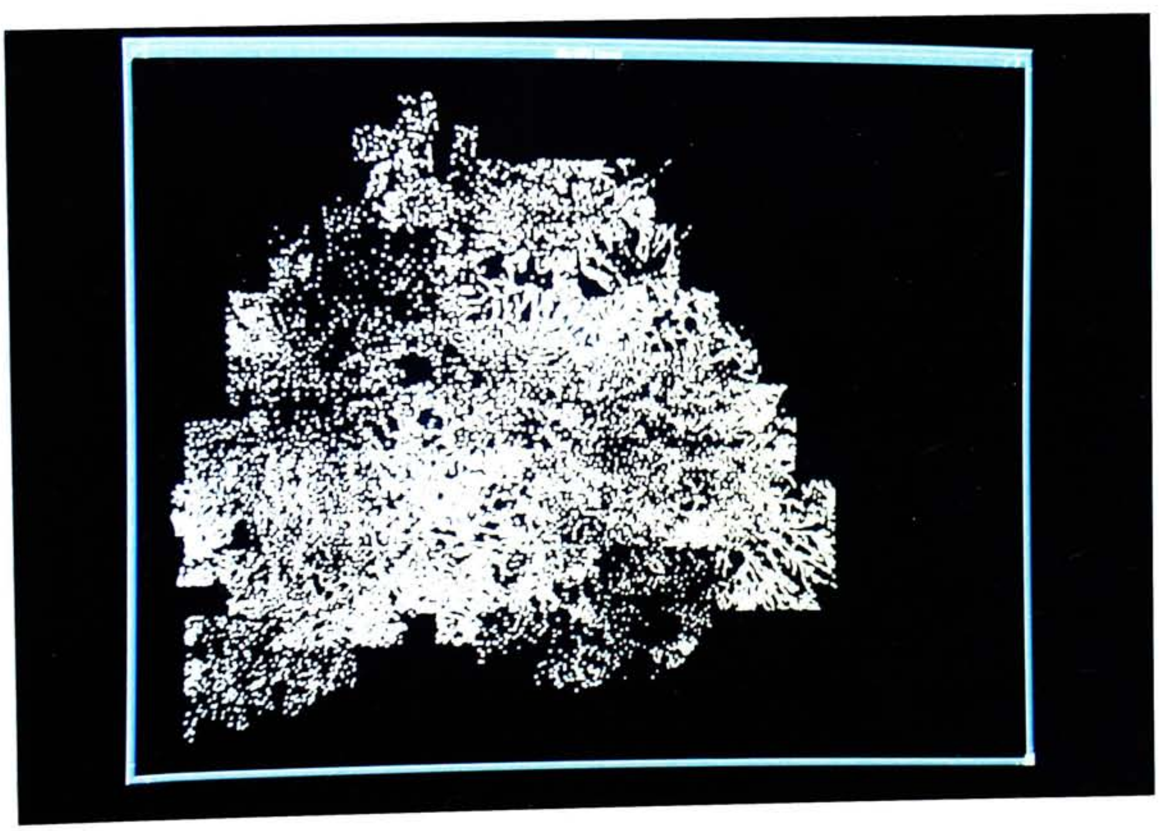


Figure 4.6 Location of spot heights and stream/ contour intersections.

| $RECNO | ALLSPOT-ID | HEIGHT | X-COORD | Y-COORD |
|---|---|---|---|---|
| 1 | 1,001 | 2.4 | 822,612.200 | 839,519.600 |
| 2 | 1,002 | 2.7 | 822,766.200 | 839,519.600 |
| 3 | 1,003 | 5.2 | 823,076.000 | 839,567.000 |
| 4 | 1,004 | 2.4 | 823,025.200 | 839,514.200 |
| 5 | 1,005 | 13.5 | 823,120.200 | 839,588.000 |
| 6 | 1,006 | 4.8 | 823,147.000 | 839,549.400 |
| 7 | 1,007 | 2.1 | 822,690.400 | 839,453.200 |
| 8 | 1,008 | 2.8 | 822,850.200 | 839,445.600 |
| 9 | 1,009 | 3.5 | 823,121.400 | 839,403.000 |
| 10 | 1,010 | 4.4 | 823,235.200 | 839,434.200 |
| 11 | 1,011 | 1.8 | 823,028.600 | 839,386.200 |
| 12 | 1,012 | 3.8 | 823,047.600 | 839,318.200 |
| 13 | 1,013 | 3.8 | 823,147.000 | 839,343.200 |
| 14 | 1,014 | 3.9 | 823,218.400 | 839,370.600 |
| 15 | 1,015 | 2.9 | 822,690.000 | 839,231.000 |
| 16 | 1,016 | 3.7 | 822,773.400 | 839,274.400 |
| 17 | 1,017 | 4.0 | 822,761.000 | 839,211.600 |
| 18 | 1,018 | 3.9 | 822,890.600 | 839,250.600 |
| 19 | 1,019 | 3.9 | 823,072.000 | 839,271.400 |
| 20 | 1,020 | 3.0 | 823,048.600 | 839,248.800 |

Table 4.1 Selected records from point attribute table of Allspot. (out of a total of 18761 records)

These map sheets, each known as a coverage, are then joined or appended together based on again the tic coordinates into one coverage named ALLSPOT (Figure 4.6). At the same time, a database file, height.txt, which consists of height values and corresponding labels or point-id of all spot locations are added to the point attribute table of ALLSPOT (allspot.pat), a database file in Arc/Info containing all information of the points - location, labels and height (Table 4.1).

With the x, y and z values of the above points, a digital terrain model (DTM) can be formed. Normally, for deriving a better approximation of the real landscape, points or locations with known heights are all taken to form a triangulated irregular network (TIN of Delaunay's methodology). The TIN is a set of adjacent, non-overlapping triangles developed from irregularly spaced points having x,y coordinates and z values. Such data structure includes topological relationships between points and their closest neighbours (ie. which points define each triangle and which triangles are adjacent to each other). As each triangle is a small facet of smooth and continuous surface, any point with unknown height can be inferred from these triangle vertices using either linear or bivariate quintic interpolation. With elevation known for the whole area, contours for any vertical interval can be formed, slope can be calculated and particularly the stream channel topography can be configurated. As such, a TIN network for all the digitized points, allspot.tin is created (Figure 4.7) by

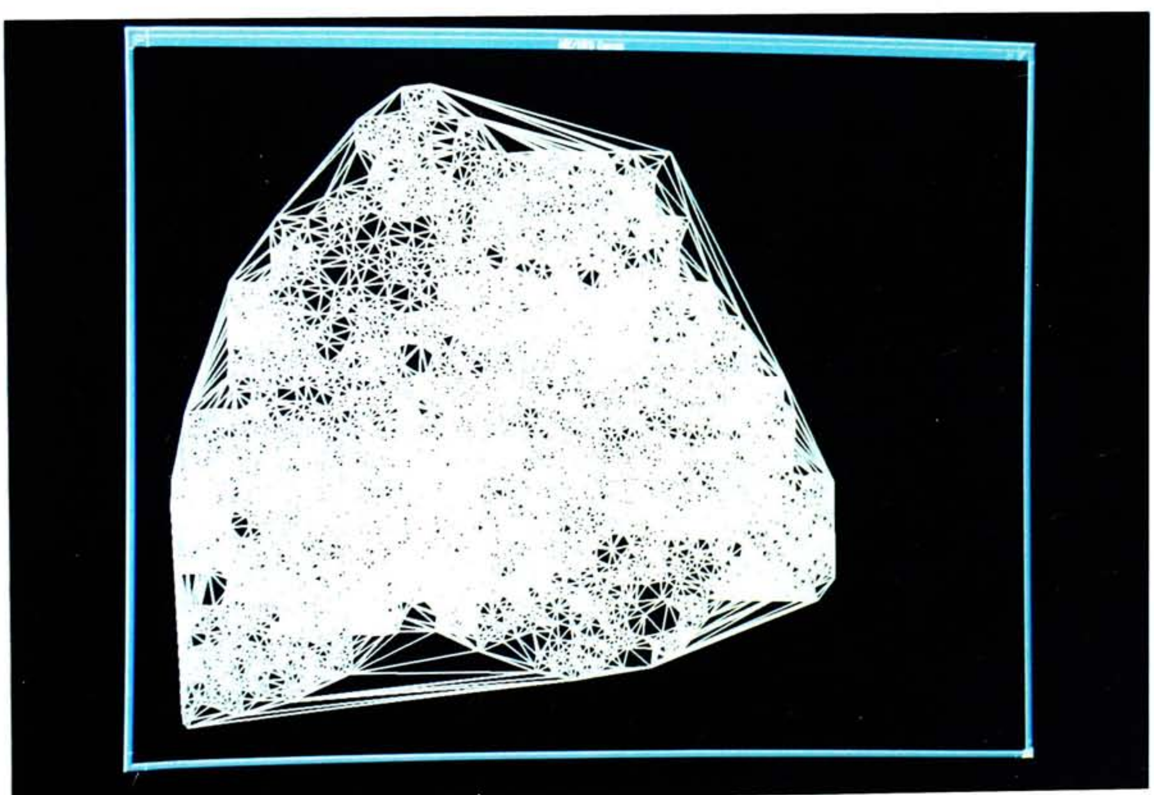


Figure 4.7 The triangulated irregular network.

using the built-in TIN functionalities in Arc/Info. This then forms the most important terrain model for future hydrological modelling.

Concerning the delineation of catchment boundary, as it is digitized from a 1:20000 map (Section 3.2.1), the 4-corner tics may not be very accurate or compatible with previous coverages. Hence, 5 tics on this map are chosen from peaks and milestones for which coordinates are also known from 1:1000 maps. This results in fairly precise representation of subcatchment boundaries and watershed lines in between two or more sets of divergent drainage systems. Even so, only about half of the boundary is delineated in the line coverage, BOUNDARY. Catchment boundary of the lower region on the source map is in fact quite arbitrarily drawn and since this project does not include the plain area, the lower portion of the studied region would better be enclosed by the 40-metre contour (Figure 4.2). From allspot.tin, the contour line, CONTOUR40 is easily derived and smoothed. Exported to the Arcad system, these two line coverages are put together and edited under the Autocad environment, thereby creating the necessary outline or template, TEMPLATE. This polygon coverage defines the extent of the whole upland catchment and its eight subcatchment areas (Table 4.2) which are useful for spatial analysis of streamflow pattern.

| $RECNO | TEMPLATE-ID | AREA | PERIMETER |
|---|---|---|---|
| 1 | 0 | -3.97066E+07 | 91,154.500 |
| 2 | 1 | 184,104.600 | 2,357.000 |
| 3 | 1 | 4182675.333 | 15,872.000 |
| 4 | 3 | 4990171.000 | 17,571.250 |
| 5 | 2 | 1547069.500 | 7,619.333 |
| 6 | 4 | 7185974.000 | 12,966.500 |
| 7 | 6 | 6506242.000 | 23,565.000 |
| 8 | 7 | 4423331.000 | 17,659.750 |
| 9 | 8 | 6562072.000 | 21,328.500 |
| 10 | 5 | 4124918.500 | 10,775.250 |

Table 4.2 The polygon attribute table of Template.
(1=Ngau Tam Mei, 2-6=Kam Tin, 7=Yuen Long, 8=Shek Po Tsuen)

## 4.5 Deriving the Stream Hydrologic Parameters

From the 1:1000 and 1:5000 base maps, a series of points along each streamlet - source, intersecting contour lines and entering culverts, are already digitized and uniquely-labelled. In other words, these points delineate the numerous short stream segments that comprise a whole stream. It is based on the information of these stream segments that further modelling could be performed. At this stage, these points have to be joined together to form linear features, most of which could be done so with a program written in C language (Appendix B), but still leaving the main streams, tributaries, and distributaries unjoined. To resolve this in a less time-consuming way, this coverage, STREAM is again exported to Arcad mainly for interactive editing using commands like extend, trim, line etc. (Figure 4.8). Upon importing back into the Arc/Info Station, it

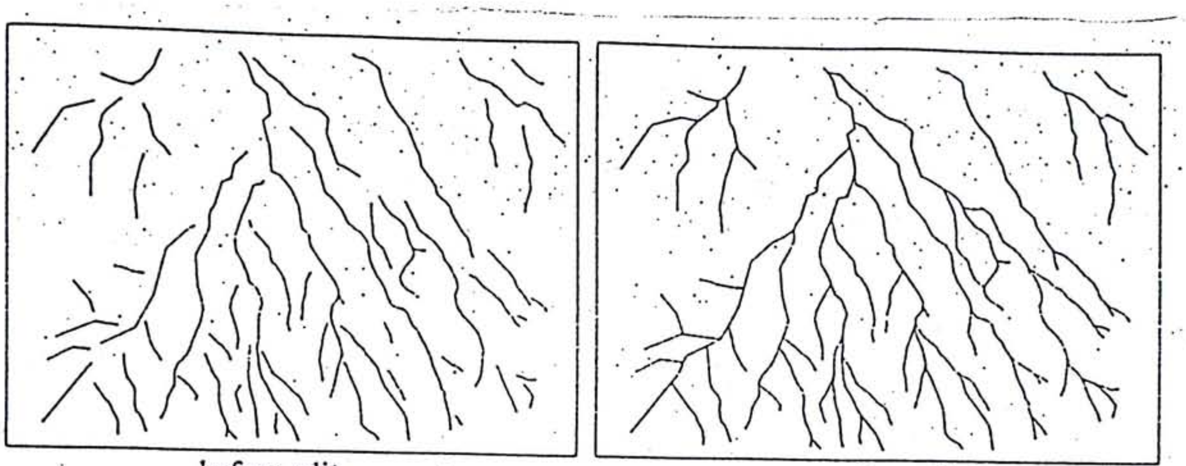



Figure 4.8 Editing of stream arcs using Arcad.

merges or overlays with the template so that attribute tables of both arc (stream) and polygon (area) features would contain information useful for subsequent analyses.

With the stream coverages (Figure 4.9) correctly cleaned in topology and ensuring the height of each starting point (from-node) being higher than corresponding ending point (to-node) for all stream segments, other attributes concerning the streams' configuration can be derived. First, using the TIN network Allspot.tin, the surfacelength (*sl*) could be found based on the height, coordinates and stream length (*le*) in the arc attribute table of STREAM. Using the same variables, the mean or *S2* slope (metres/metre) can easily be obtained by the Pythagorus Theorum (Table 4.3).

$$slope = (\sqrt{sl^2} - le^2) / le$$

| RECNO | FNODE# | TNODE# | LENGTH | SLENGTH | SLOPE | TC |
|---|---|---|---|---|---|---|
| 1 | 1,131 | 1,133 | 19.000000 | 19.000000 | 0.000000 | 0.000000 |
| 2 | 1,145 | 1,146 | 48.000000 | 51.000000 | 0.359035 | 0.569327 |
| 3 | 1,166 | 1,145 | 66.000000 | 73.000000 | 0.472620 | 0.654478 |
| 4 | 1,165 | 1,171 | 52.000000 | 54.000000 | 0.280004 | 0.666343 |
| 5 | 1,158 | 1,172 | 45.000000 | 48.000000 | 0.371184 | 0.534830 |
| 6 | 1,175 | 1,171 | 43.000000 | 45.000000 | 0.308523 | 0.554535 |
| 7 | 1,191 | 1,207 | 61.000000 | 65.000000 | 0.368032 | 0.678222 |
| 8 | 1,202 | 1,211 | 95.000000 | 101.000000 | 0.360977 | 0.961061 |
| 9 | 1,216 | 1,214 | 21.000000 | 22.000000 | 0.312259 | 0.317874 |
| 10 | 1,221 | 1,268 | 136.500000 | 145.000000 | 0.358357 | 1.274014 |
| 11 | 3 | 2 | 66.000000 | 72.000000 | 0.435985 | 0.675128 |
| 12 | 9 | 6 | 72.000000 | 82.000000 | 0.545039 | 0.662453 |
| 13 | 10 | 11 | 44.000000 | 52.000000 | 0.629837 | 0.428834 |
| 14 | 1 | 11 | 103.000000 | 352.500000 | 3.272972 | 0.437689 |
| 15 | 4 | 15 | 117.000000 | 126.000000 | 0.399704 | 1.084845 |
| 16 | 8 | 16 | 101.500000 | 121.500000 | 0.657963 | 0.802611 |
| 17 | 14 | 17 | 26.000000 | 40.000000 | 1.169129 | 0.225391 |
| 18 | 7 | 18 | 180.500000 | 207.000000 | 0.561412 | 1.329070 |
| 19 | 5 | 19 | 126.000000 | 140.000000 | 0.484322 | 1.066700 |
| 20 | 13 | 20 | 47.000000 | 53.000000 | 0.521168 | 0.485303 |

Table 4.3 Selected records from arc attribute table of Stream. (out of a total of 3098 records)

## 4.6 Modelling the Runoff Pattern

Now with slope and surfacelength available for each stream segment, time of concentration (*Tc* in minutes) (Table 4.3) can be calculated using the Kirpich's formula

$$Tc = 60 \times 0.6628 \times (sl/1000)^{0.77} / slope^{0.385}$$

This additional information to the arc attribute table of stream coverage only indicates the time required for a parcel of water to travel from the higher to lower part of each stream segment. For the derivation of cumulative time of concentration for every point along the streams to the outlet (ie. reaching the 40m contour), this has to be performed interactively using the network analysis of Arc/Info. In other words, the

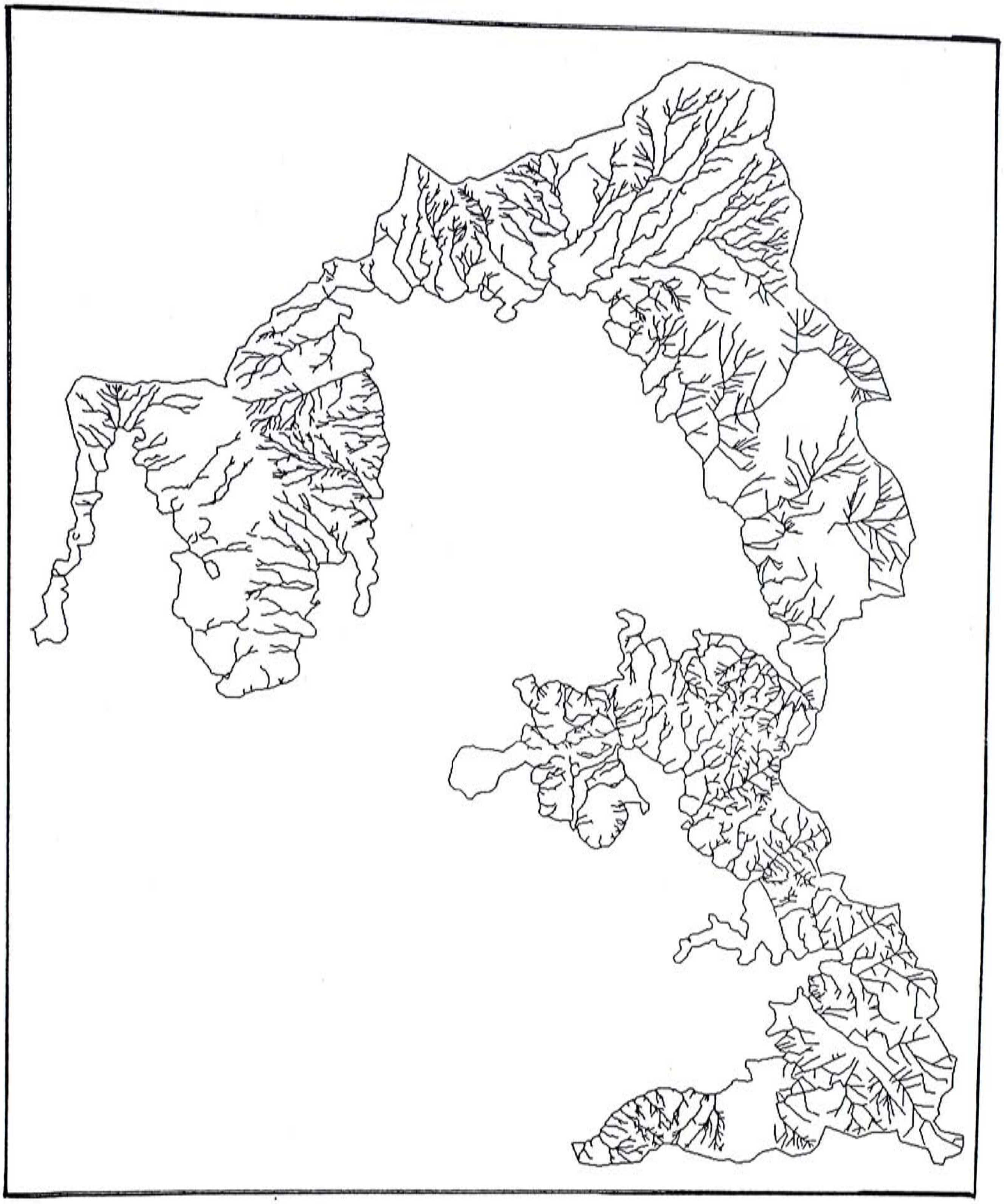
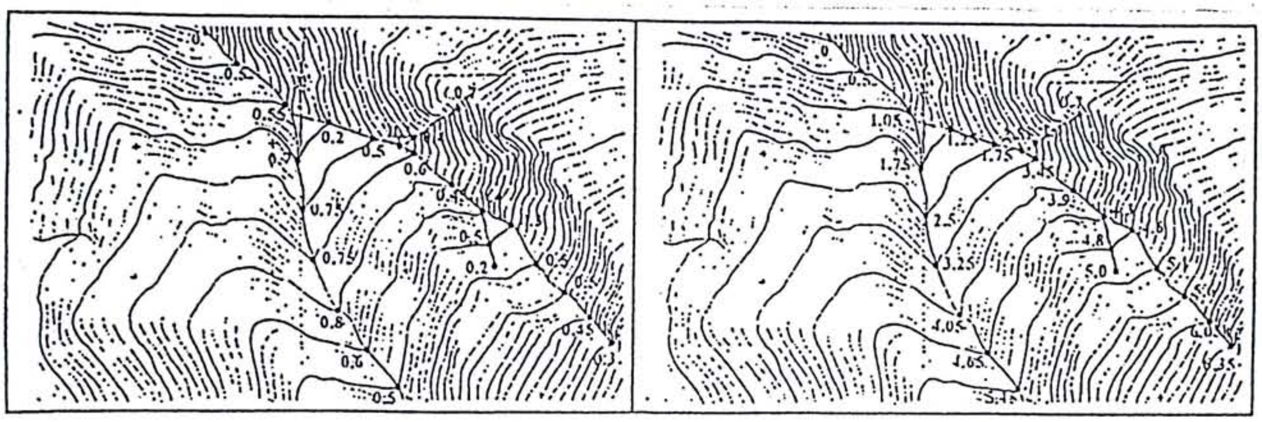


Figure 4.9 The stream network.

values of *Tc* have to be accumulated for every stream segment all from the mouth until the farthest source is reached (Figure 4.10).



Tc Cumulative Tc

Figure 4.10 Time of concentration and cumulative time of concentration. (Note the time is cumulated in an upstream direction)

By networking or routing streamflow, it means that there are fixed paths for surface flow, principally from higher to lower land, from smaller tributaries to larger ones and then to main streams. But for the calculation of cumulative time of concentration, routing will proceed upstream, being zero at the 40m contour (the outlet) and adding to larger values of *Tc* as one passes more stream segments upstream. In doing this, new variables have to be defined and combined with some existing ones from Stream.aat into a new line coverage called TIME. Therefore, the TIME.AAT (Table 4.4) would contain the following information:

(a) from-node, to-node, surfacelength and *Tc* of each stream segment as copied from STREAM.AAT;

| $RECNO | FNODE# | TNODE# | TC | IMPED | NEGIMPED | ROUTE-ID | CUMULATIVE-TC |
|---|---|---|---|---|---|---|---|
| 1 | 1,131 | 1,133 | 0.000000 | 0.250000 | -1 | 0 | 0.000000 |
| 2 | 1,145 | 1,146 | 0.569327 | 0.057143 | -1 | 691 | 9.479518 |
| 3 | 1,145 | 1,166 | 0.654478 | 0.076923 | -1 | 0 | 0.000000 |
| 4 | 1,165 | 1,171 | 0.666343 | 0.060606 | -1 | 690 | 8.632207 |
| 5 | 1,158 | 1,172 | 0.534830 | 0.058824 | -1 | 675 | 6.901041 |
| 6 | 1,175 | 1,171 | 0.554535 | 0.068966 | -1 | 689 | 8.520399 |
| 7 | 1,191 | 1,207 | 0.678222 | 0.043478 | -1 | 674 | 5.960676 |
| 8 | 1,202 | 1,211 | 0.961061 | 0.028571 | -1 | 688 | 7.586931 |
| 9 | 1,216 | 1,214 | 0.317874 | 0.142857 | -1 | 0 | 0.000000 |
| 10 | 1,221 | 1,268 | 1.274014 | 0.020833 | -1 | 673 | 4.598853 |
| 11 | 3 | 2 | 0.675128 | 0.033333 | -1 | 1 | 0.675128 |
| 12 | 9 | 6 | 0.662453 | 0.033333 | -1 | 2 | 0.662453 |
| 13 | 10 | 11 | 0.428834 | 0.035714 | -1 | 14 | 5.513575 |
| 14 | 11 | 1 | 0.437689 | 0.004348 | -1 | 0 | 0.000000 |
| 15 | 4 | 15 | 1.084845 | 0.022727 | -1 | 4 | 2.169950 |
| 16 | 8 | 16 | 0.802611 | 0.015152 | -1 | 9 | 3.774739 |
| 17 | 14 | 17 | 0.225391 | 0.033333 | -1 | 3 | 0.830624 |
| 18 | 7 | 18 | 1.329070 | 0.010000 | -1 | 8 | 3.707037 |
| 19 | 5 | 19 | 1.066700 | 0.016667 | -1 | 6 | 2.207126 |
| 20 | 13 | 20 | 0.485303 | 0.041667 | -1 | 5 | 1.467516 |
| 21 | 11 | 21 | 0.765588 | 0.016667 | -1 | 14 | 5.084740 |
| 22 | 12 | 22 | 0.635520 | 0.026316 | -1 | 13 | 4.472882 |
| 23 | 15 | 24 | 0.315266 | 0.111111 | -1 | 4 | 1.085105 |
| 24 | 19 | 25 | 0.184878 | 0.166667 | -1 | 6 | 1.140425 |
| 25 | 18 | 26 | 0.229526 | 0.166667 | -1 | 8 | 2.377968 |

Table 4.4 Selected records from arc attribute table of Time. (out of a total of 3098 records)

(b) a negative impedance value (negimped = -1) is assigned to all arcs beginning at the from-node and ending at the to-node. Negative is identified as barrier to movement in Arc/Info's networking, so that routing will not occur in the downstream direction;

(c) Imped, a parameter of restriction degree, sets criteria for the optimum routing path in the upstream direction, ie. for all arcs beginning at the to-node and ending at the from-node. It is calculated as

$$1 / [(\textit{from-node's height}) - (\textit{to-node's height})]$$

so that the smaller the impedance or the greater the height difference, the more likely will water flow along that path.

Meanwhile, by extracting all digitzed points (ie. all from- and to-nodes) from the stream coverage, a point coverage named STOPS is formed. After reading STOPS into the network as described above, a route can be selected interactively by choosing a starting and an ending point, usually one point at the outlet and another the farthest source of the stream tributaries. For all routes selection, the cumulative demand, ie. Cumulative-*Tc* for all points in the coverage whose values are accumulated from previous points in the route will be calculated. By the command writeroute, the Route-number and Cumulative-*Tc* values would be written and saved to TIME.AAT (Table 4.4).

Finally, after relating the Cumulative-*Tc* values to all the points in STOPS, lines of equal Cumulative-*Tc* values called isochrones could be derived using the same principles and methods as building a DTM with TIN. Just like generating contours from spot heights, a coverage named ISOCHRONES (Table 4.5) with 5-minute intervals is built upon STOPS and Stops.tin.

To derive distinct flood hazard regions, ISOCHRONES is overlaid with TEMPLATE to form FLOW, polygons of unique flow regions (Figure 5.8). Based on Clark's Time-Area Hydrograph Method, the

| RECNO | LENGTH | ISOCHRONES-ID | CUMULATIVE-TC |
|---|---|---|---|
| 1 | 260.000 | 5 | 5.000 |
| 2 | 943.500 | 15 | 15.000 |
| 3 | 3,030.000 | 5 | 5.000 |
| 4 | 1,309.333 | 15 | 15.000 |
| 5 | 446.000 | 5 | 5.000 |
| 6 | 1,813.333 | 10 | 10.000 |
| 7 | 2,641.000 | 10 | 10.000 |
| 8 | 1,859.667 | 5 | 5.000 |
| 9 | 4,142.667 | 5 | 5.000 |
| 10 | 191.500 | 5 | 5.000 |
| 11 | 40.000 | 5 | 5.000 |
| 12 | 0.400 | 5 | 5.000 |
| 13 | 119.500 | 10 | 10.000 |
| 14 | 477.000 | 5 | 5.000 |
| 15 | 411.500 | 15 | 15.000 |
| 16 | 261.000 | 15 | 15.000 |
| 17 | 458.000 | 5 | 5.000 |
| 18 | 123.000 | 10 | 10.000 |
| 19 | 34.000 | 10 | 10.000 |
| 20 | 588.500 | 10 | 10.000 |

Table 4.5 Selected records from arc attribute table of Isochrone. (out of a total of 95 records)

amount of surface flow for every time interval in each polygon or region is found by multiplying its area with the 5-minute typhoon rainfall figures (Appendix C and Appendix D), the procedure as mentioned in section 4.1. Hence, by cumulating or routing the netflow of every unit time throughout the region, flood hazard maps of t1, t2 ... tn could be produced.

□

# CHAPTER 5 RESULTS AND ANALYSIS

## 5.1 The Topographic Data Base

### 5.1.1 The Overall Studied Area

The upland catchment of Yuen Long and Kam Tin drainage basin as defined by the 40 metre contour has a total area of 39.7 $km^2$, consisting of 4 major catchments and 5 smaller sub-catchments (Figure 5.1) Within this region, 3098 stream segments have been digitized, each being about 2 metres in horizontal length. In general, streams are short but numerous, with the highest order exceeding the $5^{th}$ rank according to Strahler's stream ordering (Strahler, 1970). For the greater part of the area, a dendritic pattern exists in which tributaries join each other obliquely. Only near the Tai Lam Chung area, ie. in the southern part of the study region is a rectangular drainage pattern found (Figure 4.6). Stream channel slopes vary in different parts of the region (Table 5.1). About 58% belong to moderate while 32% are classified as gentle. Most of these lie below the 100 metre height level where the flood plain begins to emerge. Near the peaks, though the area is less extensive, slopes are very steep indeed with about 10% over 30 degrees (Table 5.1). In general, the whole area has a very sharp break of slope at around 50 metre in height.

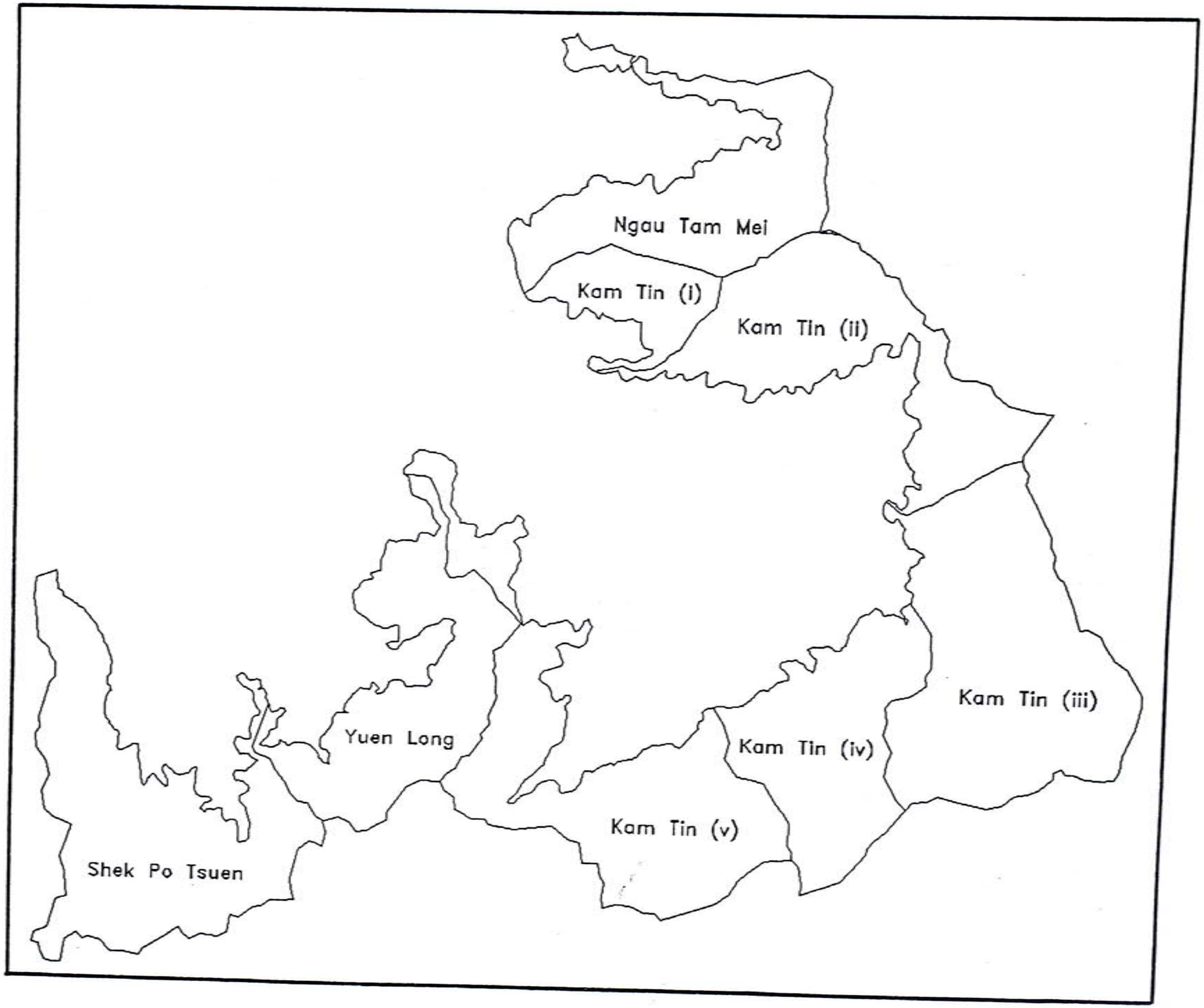



Figure 5.1 The study area with its subcatchment division.

| slope code | 1 | 2 | 3 | 4 | total |
|---|---|---|---|---|---|
| slope type | gentle | moderate | steep | very steep | |
| gradient | < 0.27 | 0.27 - 0.56 | 0.56 - 1.00 | > 1.00 | |
| degrees | < 15 | 15 - 30 | 30 - 45 | > 45 | |
| stream surface -length (km) | 106.88 | 190.87 | 26.24 | 6.57 | 330.56 |
| % total length | 32.33 | 57.74 | 7.94 | 1.99 | 100 |

Table 5.1 Classification and percentage of slope types.

## 5.1.2 Spatial Variation of Catchment Area and Streamlength

The Kam Tin catchment is the largest and the most important part of the studied area, covering an area of 24.35 $km^2$ which is over 61% of the total area (Table 5.2). Hydrological data from both rain gauge and

| CATCHMENT | AREA ($km^2$) | % AREA | STREAM LENGTH (km) | % STREAM LENGTH | STREAM DENSITY ($km/km^2$) |
|---|---|---|---|---|---|
| 1. Ngau Tam Mei | 4.18 | 10.99 | 20.84 | 6.3 | 4.99 |
| 2. Kam Tin | 24.35 | 61.34 | 208.67 | 63.13 | 8.57 |
| subcatchment i | 1.55 | 3.90 | 12.44 | 3.76 | 8.03 |
| subcatchment ii | 4.99 | 12.57 | 49.53 | 14.99 | 9.93 |
| subcatchment iii | 7.19 | 18.11 | 59.04 | 17.86 | 8.21 |
| subcatchment iv | 4.12 | 10.38 | 32.87 | 9.94 | 7.98 |
| subcatchment v | 6.50 | 16.38 | 54.79 | 16.58 | 8.43 |
| 3. Yuen Long | 4.42 | 11.14 | 43.21 | 13.07 | 9.78 |
| 4. Shek Po Tsuen | 6.56 | 16.53 | 57.84 | 17.5 | 8.82 |
| TOTAL | 39.71 | 100 | 330.56 | 100 | mean 8.04 |

Table 5.2 Streamlength and area relationship of individual catchments.

stream gauge are also found within this catchment. This part contains the most abundant stream courses, about 63% of all studied stream segments (Table 5.2). The other three major catchments - Shek Po Tsuen, Yuen Long and Ngau Tam Mei, though smaller in area and having fewer streams, do not deviate much in stream density, averaging around 8 km of stream surfacelength per square kilometre. Only the Ngau Tam Mei catchment in the north has a lower stream distribution, of about 5 $km/km^2$.

### 5.1.3 Spatial Variation of Stream Channel Slope

Stream channel slopes, implying also the overall terrain, in general become gentler in a north-south direction in the studied catchments. Mean slopes are in the range of 23° to 24° for the Ngau Tam Mei and most parts of Kam Tin catchments in the north while they go down to about 16° for those catchments in the south, especially the Yuen Long catchment (Table 5.3). Very steep slopes reaching above 60° can be found near the peaks everywhere except in the Yuen Long catchment where only small hills with undulating relief occur.

| CATCHMENT | MEAN SLOPE (DEGREES) | MAXIMUM SLOPE (DEGREES) | % SLOPE OF STUDIED REGION CLASSIFIED AS | | | |
|---|---|---|---|---|---|---|
| | | | GENTLE | MODERATE | STEEP | VERY STEEP |
| Ngau Tam Mei | 23.3 | 73.01 | 1.88 | 8.67 | 4.94 | 15.12 |
| Kam Tin | 20.45 | 87.4 | 60.79 | 61.28 | 82.18 | 78.52 |
| subcatchment i | 24.68 | 69.37 | 1.9 | 4.38 | 5.48 | 9.46 |
| subcatchment ii | 23.47 | 87.4 | 9.04 | 16.65 | 24.37 | 25.75 |
| subcatchment iii | 21.48 | 78.54 | 21.68 | 12.36 | 39.12 | 30.42 |
| subcatchment iv | 16.08 | 65.78 | 10.35 | 9.88 | 9.8 | 5.74 |
| subcatchment v | 16.53 | 70.55 | 17.82 | 18.01 | 3.41 | 7.15 |
| Yuen Long | 15.19 | 40.37 | 15.8 | 13.33 | 3.37 | 0 |
| Shek Po Tsuen | 17.82 | 68.63 | 21.53 | 16.72 | 9.51 | 6.36 |
| | | TOTAL = | 100 | 100 | 100 | 100 |

Table 5.3 Slope parameters.

On the other hand, by comparing the proportion of stream surfacelength for each slope type in individual catchments to the total surfacelength of each slope type for the whole studied region (Table 5.3), it is readily seen that a much greater proportion of steep to very steep slopes (82% and 78.5% respectively) occur in the Kam Tin catchment, in particular subcatchments ii and iii which is far more than the proportion of total streamlength (63%) it occupies. This reflects the rugged topography of prominent peaks like Tai Mo Shan, Kwun Yam Shan, Tai To Yan and Kai Kung Leng. By contrast, the Yuen Long and Shek Po Tsuen catchments are characterized by more gentle to moderate slopes, the former having no slope greater than 45°. Hence, gentle to steep slopes are not evenly distributed. In the north and east, streams are more numerous, running on steeper terrain and longer distance before reaching the plain, while towards the southwestern direction, streams are shorter, slopes are gentler and flood plain becomes more extensive.

### 5.1.4 Time of Concentration

As time of concentration is directly proportional to stream surfacelength but inversely proportional to slope gradient, streamflow within the Ngau Tam Mei catchment should therefore be the quickest with its shorter streamlength, lower stream density and steeper slopes when compared to catchments in the south. However, results show that (Figure 5.2) the isochrone pattern in this area shows no great difference to those in Yuen Long and Shek Po Tsuen catchments. By looking at the percentage area occupied by each isochrone group in different subcatchments (Table 5.4), just slightly more areas in the Ngau Tam Mei catchment belong to the lower range classes, ie. 0-5 and 5-10 minutes when compared to those of Yuen Long and Shek Po Tsuen catchments. The difference is no more than 5% for comparing any isochrone class between these catchments. This may be due to the fact that in the latter catchments, a rectangular drainage pattern, in which tributaries join each other nearly orthogonally, enables more direct and speedy flow with the time span catching up with the northern part. On the other hand, though the steepest slopes are found in the Kam Tin catchment, the far larger area, longer streamlength and more intricate dendritic drainage network here all contribute to higher concentration times. The greatest time, over 30 minutes, is about double of that for all other catchments. In spite of this, concentration time overall speaking is regarded as short, implying that when heavy storms occur, enormous streamflow amounts will reach the upland/lowland frontier all within half an hour. And for storms lasting for a day or two, the amount could be considerable, causing severe flooding which will be exemplified in the next few sections.

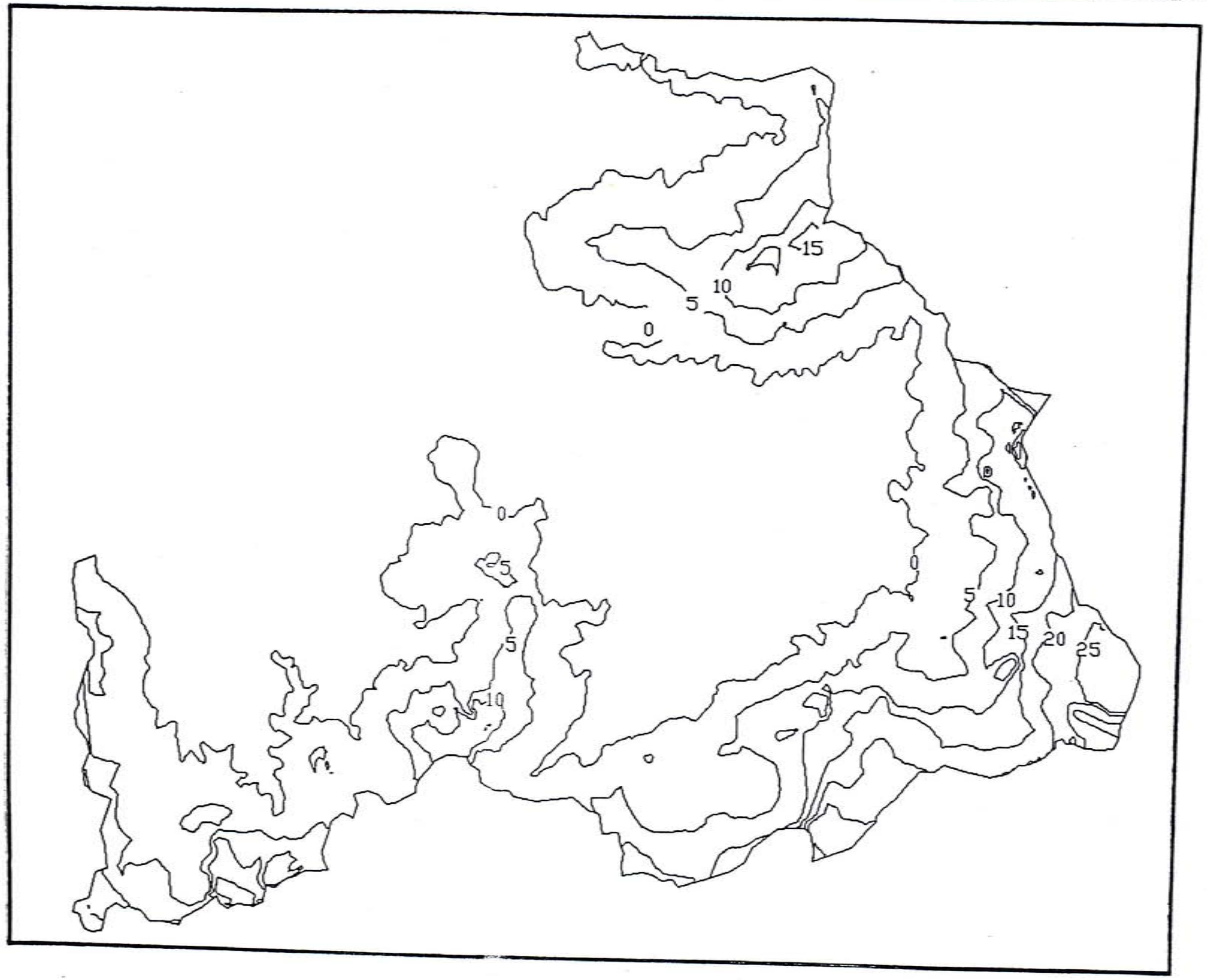



Figure 5.2 The isochrone map of 5-minute interval.

| CATCHMENTS | FLOW AREA BOUNDED IN BETWEEN TIME OF CONCENTRATION (MINUTES) OF | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | 0 - 5 | 5 - 10 | 10 - 15 | 15 - 20 | 20 - 25 | 25 - 30 | Total |
| Ngau Tam Mei | 3.19 (72.96) | 0.98 (22.46) | 0.20 (4.51) | 0.003 (0.07) | nil | nil | 4.37 |
| Kam Tin | 10.85 (44.85) | 6.09 (25.15) | 3.32 (13.73) | 1.66 (6.87) | 0.57 (2.37) | 1.70 (7.02) | 24.20 |
| subcatchment i | 0.99 (64.30) | 0.54 (34.61) | 0.02 (1.10) | nil | nil | nil | 1.55 |
| subcatchment ii | 2.45 (50.02) | 1.34 (27.45) | 1.09 (22.30) | 0.01 (0.23) | nil | nil | 4.89 |
| subcatchment iii | 1.40 (19.70) | 1.38 (19.50) | 1.66 (23.42) | 1.22 (17.17) | 0.003 (0.04) | 1.43 (20.18) | 7.10 |
| subcatchment iv | 1.29 (31.37) | 1.07 (25.87) | 0.53 (12.73) | 0.43 (10.38) | 0.54 (13.19) | 0.27 (6.47) | 4.13 |
| subcatchment v | 4.72 (72.51) | 1.76 (27.00) | 0.03 (0.43) | 0.004 (0.04) | nil | nil | 6.51 |
| Yuen Long | 3.18 (71.87) | 0.88 (19.92) | 0.36 (8.18) | 0.001 (0.02) | nil | nil | 4.42 |
| Shek Po Tsuen | 4.48 (68.30) | 1.53 (23.38) | 0.46 (6.93) | 0.09 (1.39) | nil | nil | 6.56 |
| Total | 21.70 | 9.48 | 4.34 | 1.76 | 0.57 | 1.70 | 39.55 |

Table 5.4 Flow area differentiated by varying concentration time.

## 5.2 The Hydrometeorological Data

### 5.2.1 Derived Hydrographs From Rain Gauge Records

Using the Time-Area Hydrograph Method discussed in Chapter 2 and 4, hydrographs are derived for the five typhoons separately (Figure 5.3). For all cases, the original lines fluctuate very frequently with many small crests and troughs. This is mainly because of the very detailed rainfall records at just 5-minute intervals. Within the whole storm, there may be numerous occurrences of 0mm of rain and these reduce the total value at the end (Appendix C). If stream volume at 5-minute intervals is shown, this kind of noise (sharp rises and falls of lines) seems inevitable. Consequently, to get a clearer picture of streamflow pattern, these lines need to be generalized (Figure 5.4) with stream velocity in terms of per hour and flow volume expressed in mega litres consistent with WSD hydrographs unit.

### 5.2.2 Stream Gauge Data

Hydrographs generated from stream gauges can be used as checks on the validity of the derived hydrographs. In the studied region, such references could only be made to one stream gauge in Kam Tin from which data are more reliable. But before any comparison is to be made, these stream gauge-generated hydrographs (Appendix E) have to be

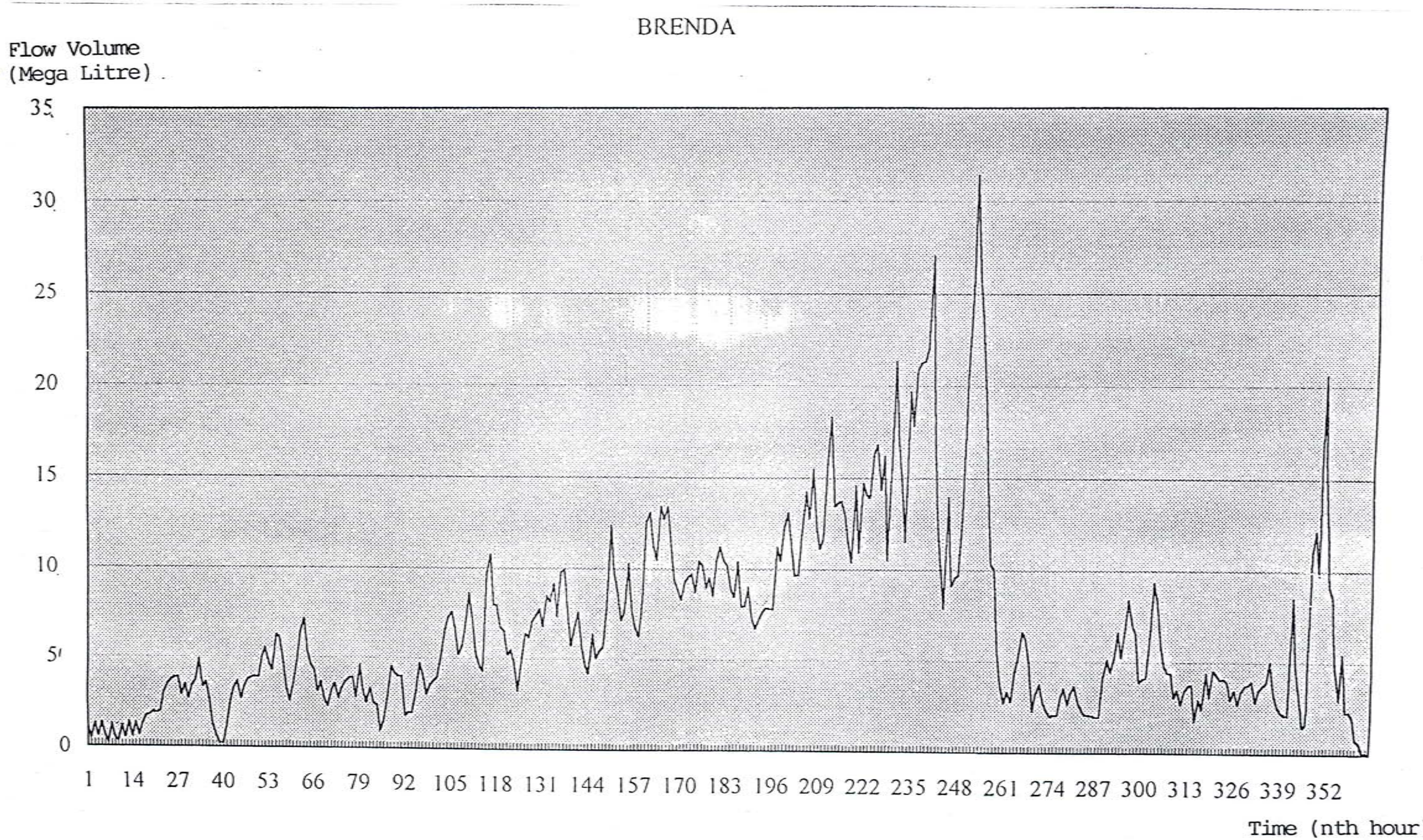



Figure 5.3 Hydrographs produced by time-area method.

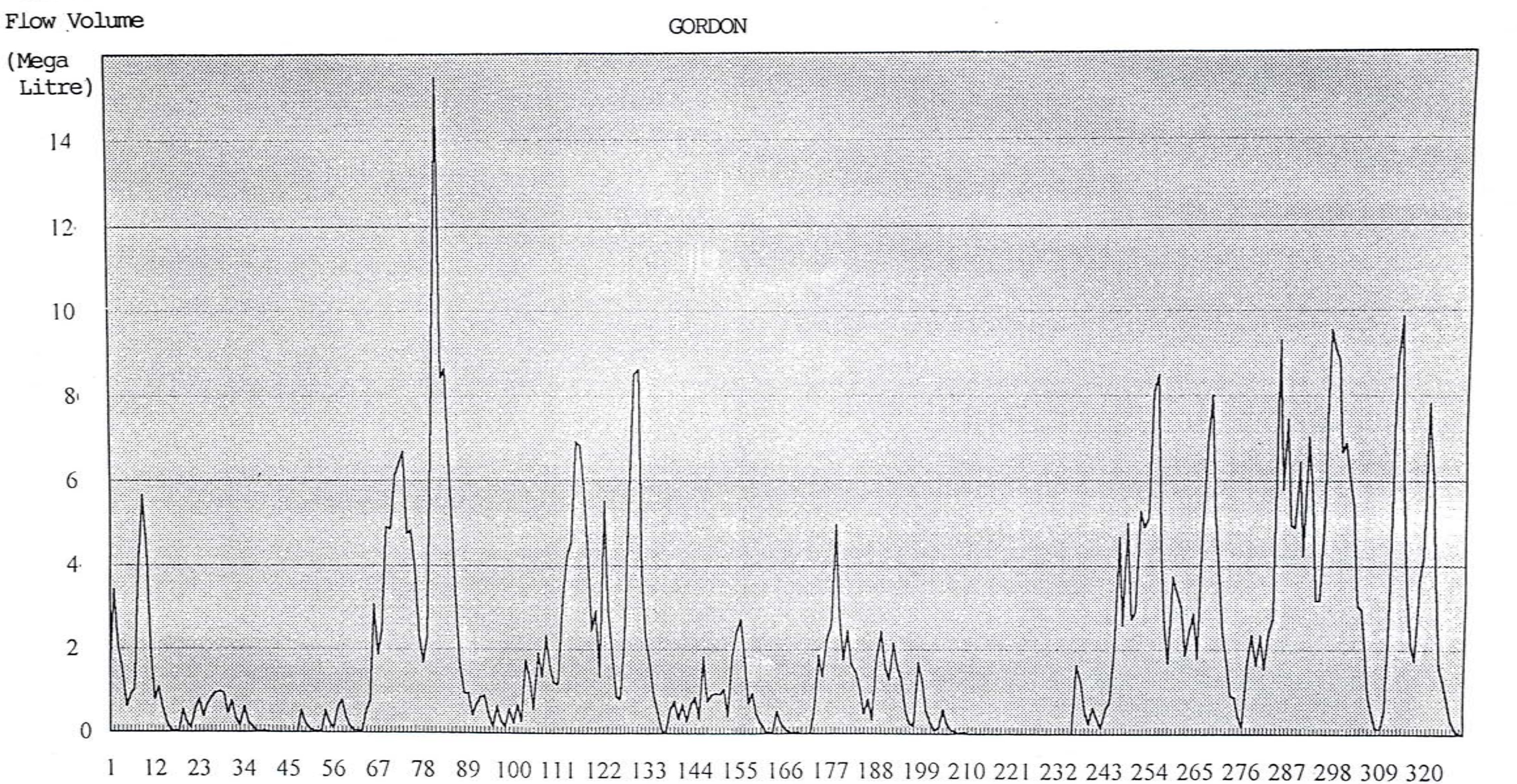



Figure 5.3 (cont'd)

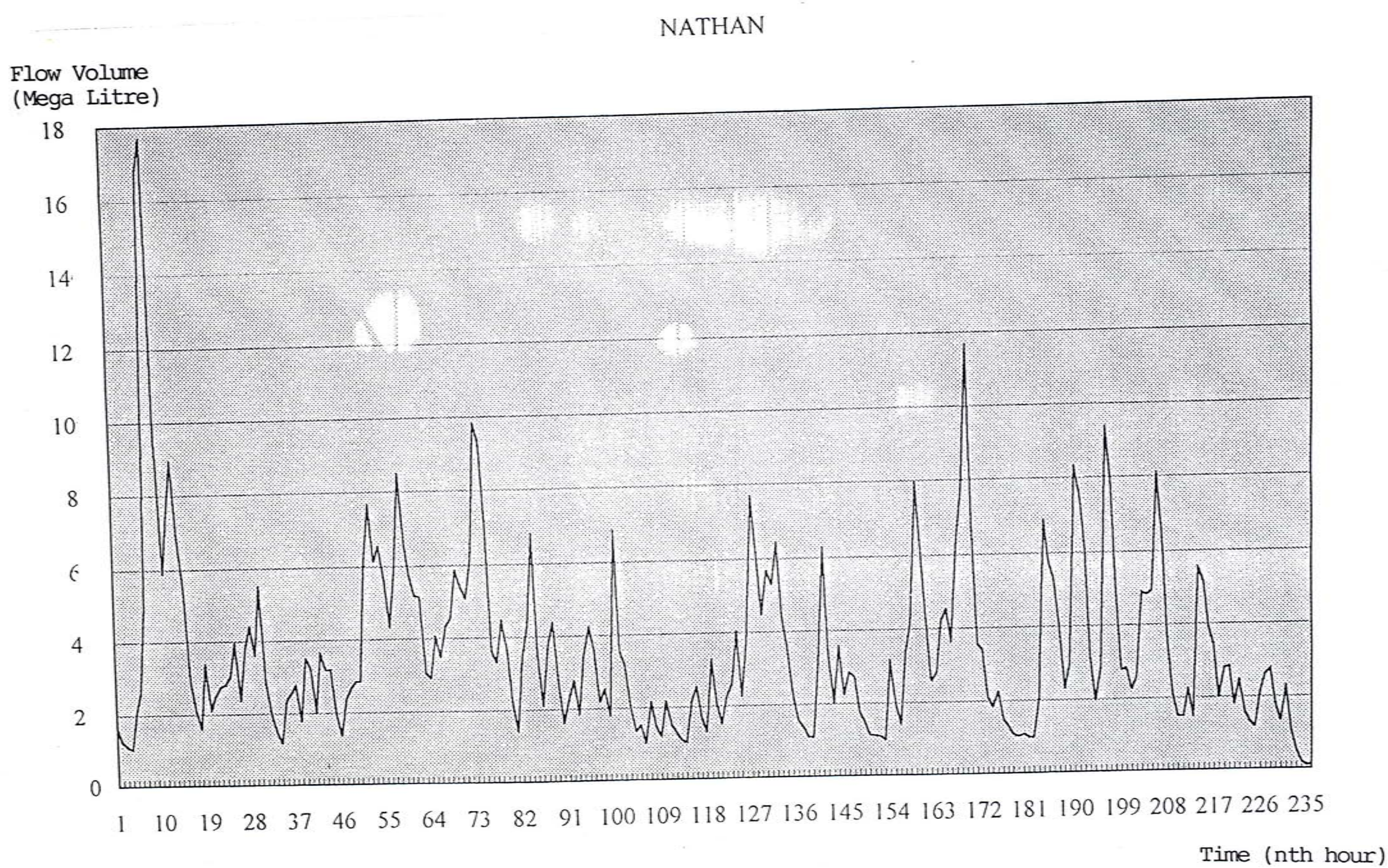



Figure 5.3 (cont'd)

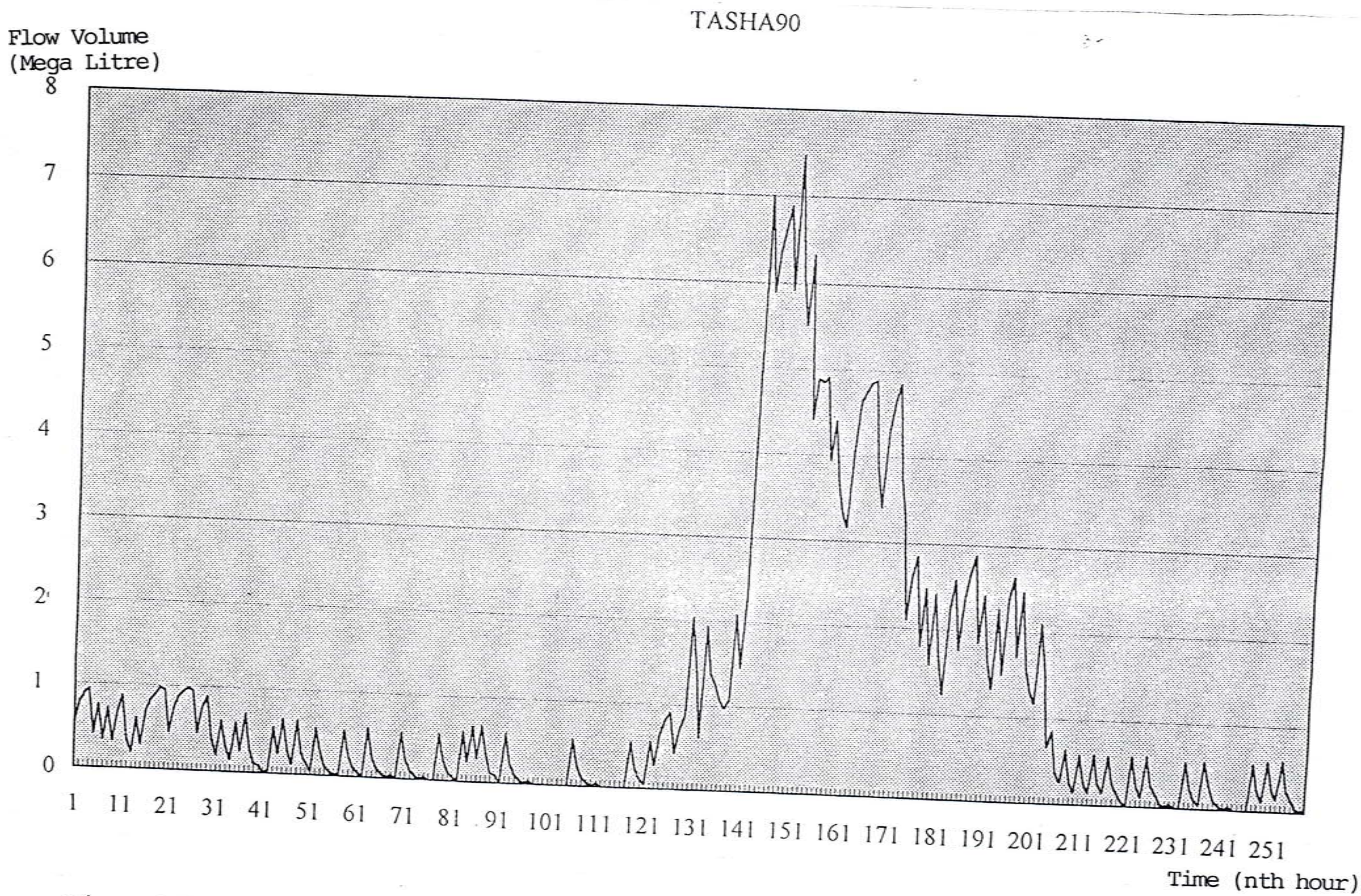



Figure 5.3 (cont'd)

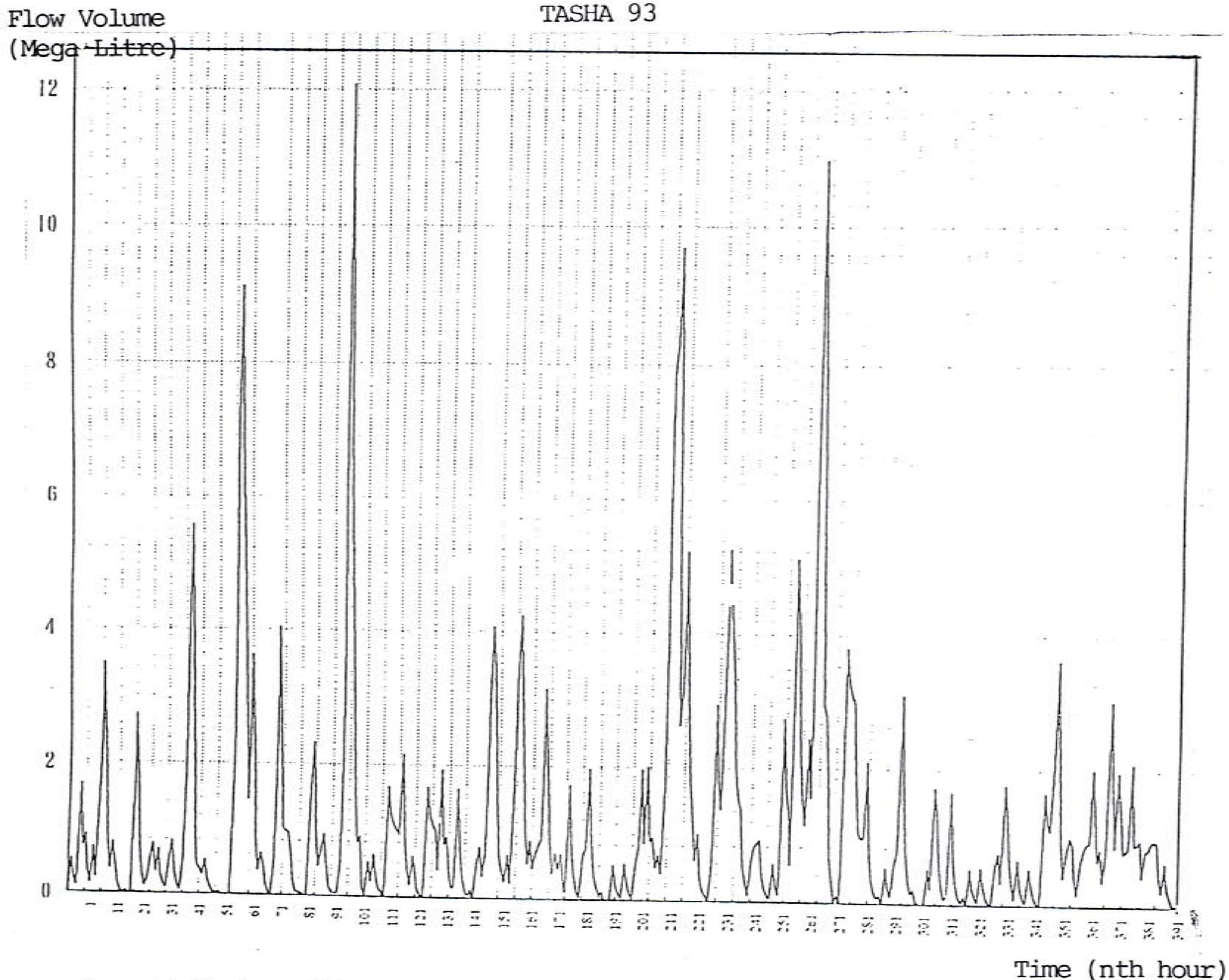



Figure 5.3 (cont'd)

refined. First, water levels passing the gauge at different times of a day are redetermined, so that rise and falls of lines indicate peaks and troughs accordingly. Second, since comparison is made to time-area hydrographs of per hour velocity, the abscissa has to be reconstructed on the same basis. Finally, from the rating tables (Appendix F) provided by the Water Services Department, flow volume in mega litres could be determined from the varying water levels (Appendix G). With all these done, hydrographs are modified from the original ones for each of the studied storm (Figure 5.4).

Nevertheless, to compare the hydrographs from WSD data with the derived time-area unit hydrographs, several discrepancies and problems have to be noted beforehand. To start with, although this is considered the most reliable and sole information source of streamflow, the stream gauge configuration is such that lines could not continue to be drawn up or down when water level reaches more than 1.25 metres, resulting in thickened zig-zag curves as exemplified in Figure 5.5, especially during very heavy storms. Sometimes, the magnitude is so large and sudden that the pen could not adjust properly and result in thickened lines. These cases already indicate erroneous readings and so accurate streamflow volume could not be obtained. Next, in the rating tables, flow volumes are calculated for a water level up to 3.99 metres only. So if even higher water level marks are recorded as in case of Typhoon Brenda, the highest mark being 4.355 metres, the flow volume has to be estimated. In fact, as pointed out by WSD officers-in-charge, very rough estimates of stream flow volume are already starting at water level higher than 3.6 metres.

Most important of all, the Kam Tin stream gauge is supposed to measure water flow from the Kam Tin catchment only whereas the hydrographs derived in this study refer to the whole upland catchment of Yuen Long and Kam Tin drainage basin. Therefore it is necessary to consider the proportion of area that Kam Tin catchment occupies. Even so, since the stream gauge is not located at the 40 metres contour but far beyond it in the lowland area at about 5 metres high (Figure 5.1), much larger volume of stream flow will be expected at the gauge point. Although such excess may be compensated by artificial diversion of flow to the Tai Lam Chung Reservoir area in the uplands, very precise flow volume contributed just by upland regions seems difficult to verify because of these uncertainties or discrepancies between the two sets of data.

### 5.2.3 Analyses of Time-Area Hydrographs

#### 5.2.3.1 Hydrograph Shapes

As derived time-area hydrographs are based on per 5-minute rain gauge records whereas stream gauge hydrographs are based on per 15-minute records, although both are converted to hourly record when putting together for comparison, it is expected that the former with more detail will have more irregularities with numerous small peaks and troughs (Figure 5.4).

It is found that only in severe storms of high rain intensity do major rises and falls of the two graphs have closer approximation. In Typhoon Brenda (Figure 5.4a), the shape of the two graphs corresponds quite well especially after the peak at about 000 hour on 21 May but with a time lag of about 2 hours. In fact, this, among all studied typhoons, has the closest pattern of the two hydrographs. Similarly, for Typhoon Gordon (Figure 5.4b), both graphs contain 4 major peaks but with a varying but greater time lag as time increases. Nevertheless, for other storms, it is difficult to identify a close correlation of the two graphs. In Typhoon Nathan (Figure 5.4c) very different hydrograph shapes occur especially at the several peaks of the storm whereas even more divergent shapes occur in Typhoon Tasha of 1993 (Figure 5.4e). For Typhoon Tasha of 1990

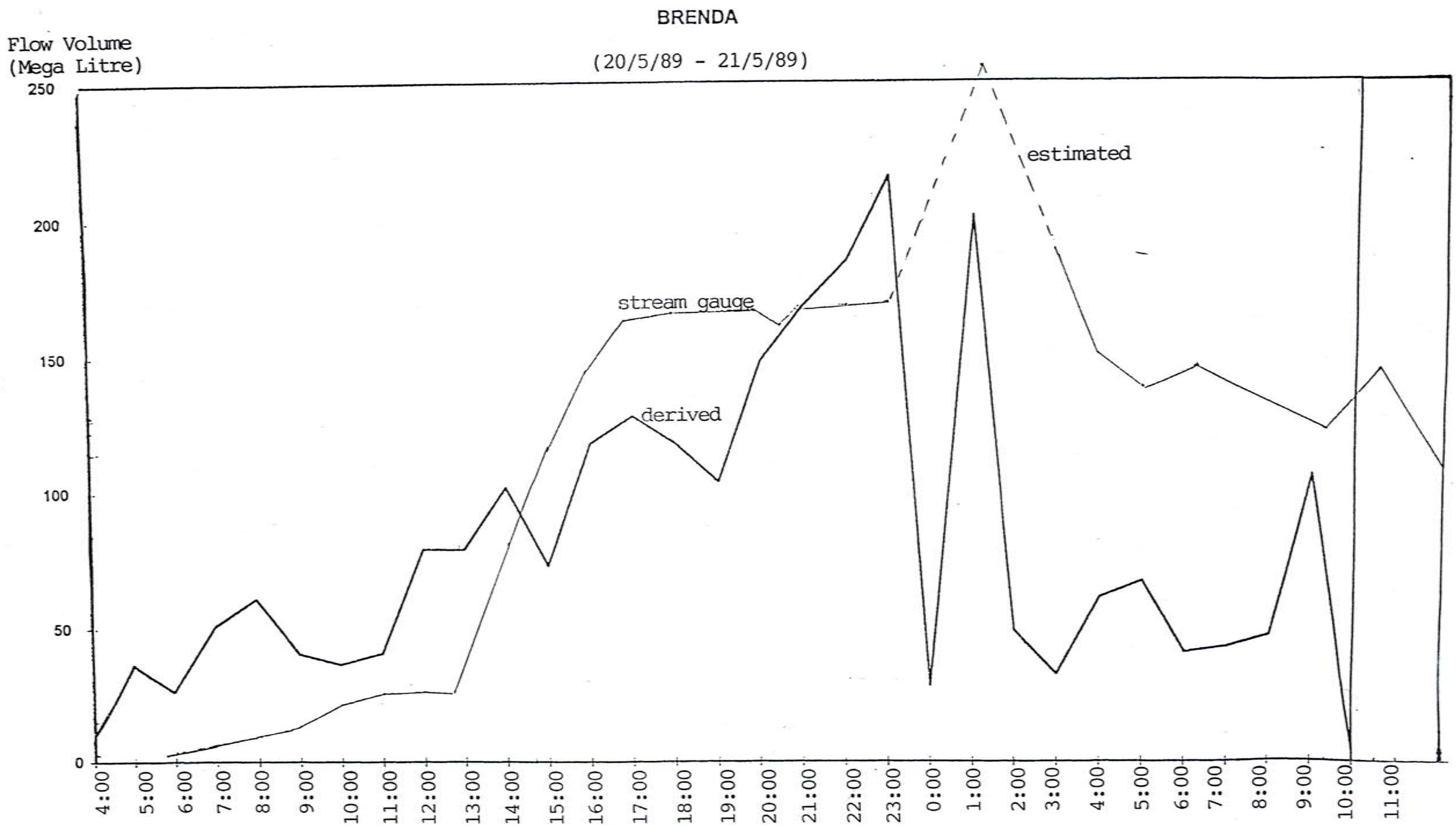
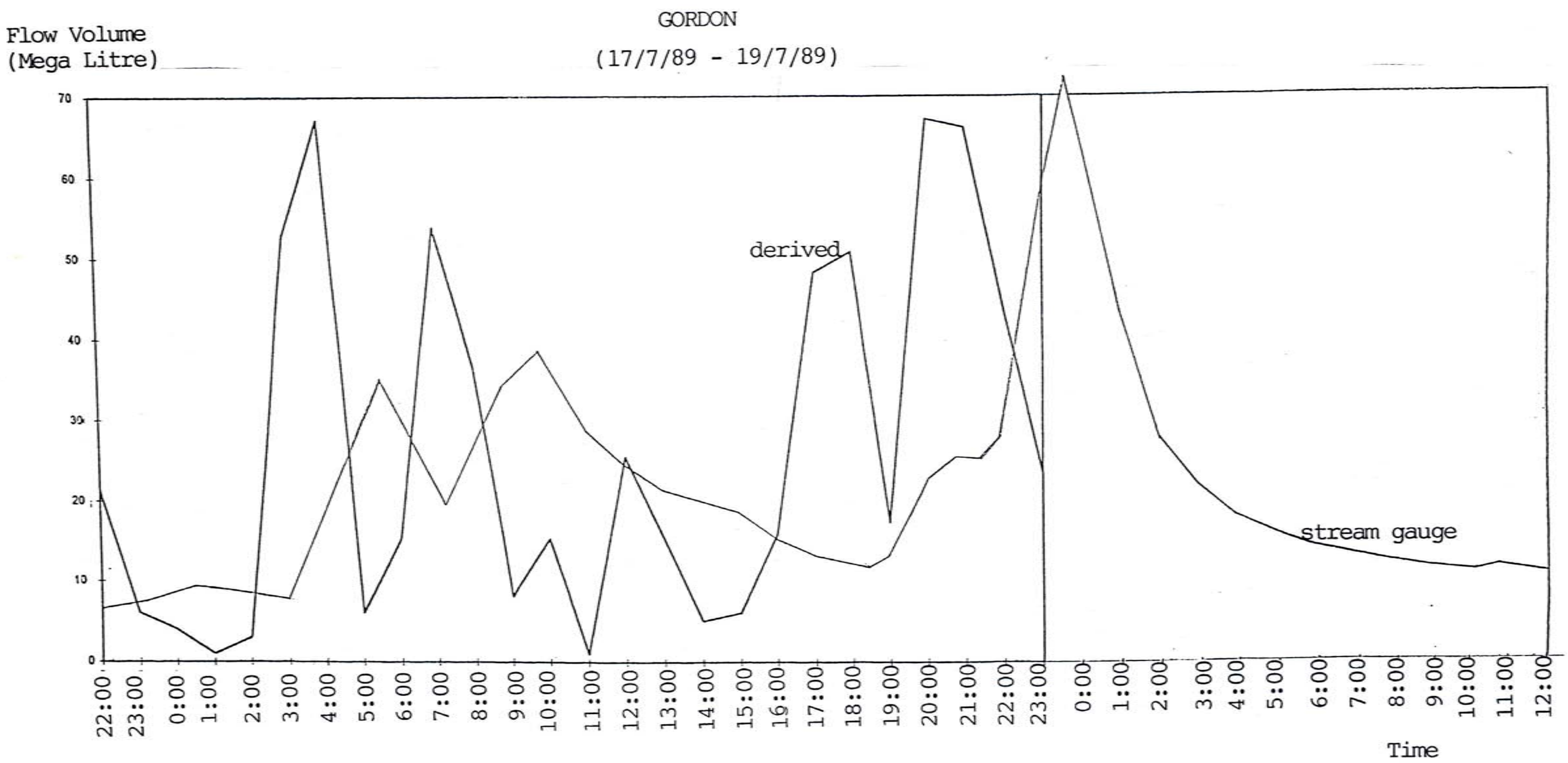



Figure 5.4 Generalized Hydrographs produced by Time-Area Method.




Fogure 5.4 (Cont'd)

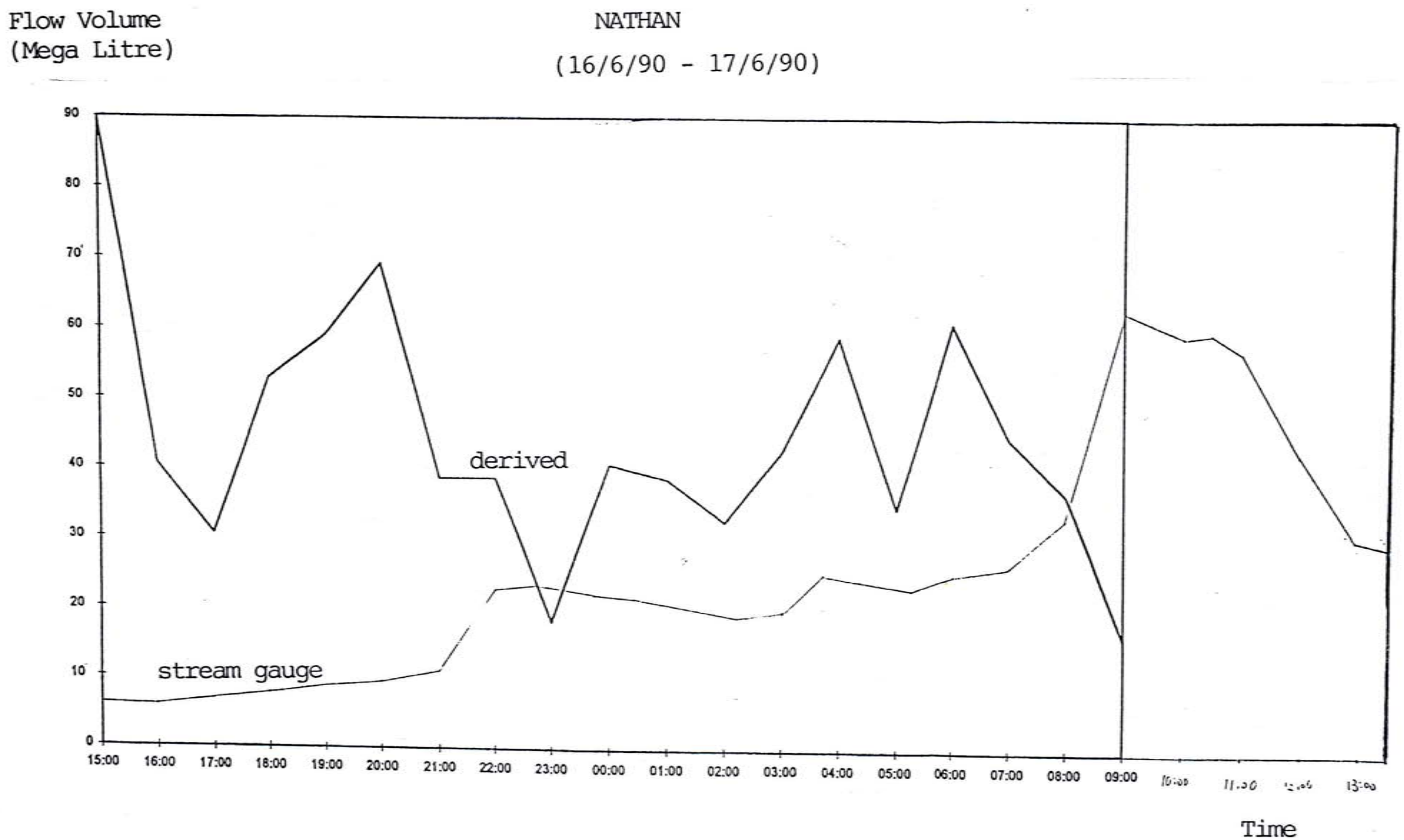



Figure 5.4 (Cont'd)

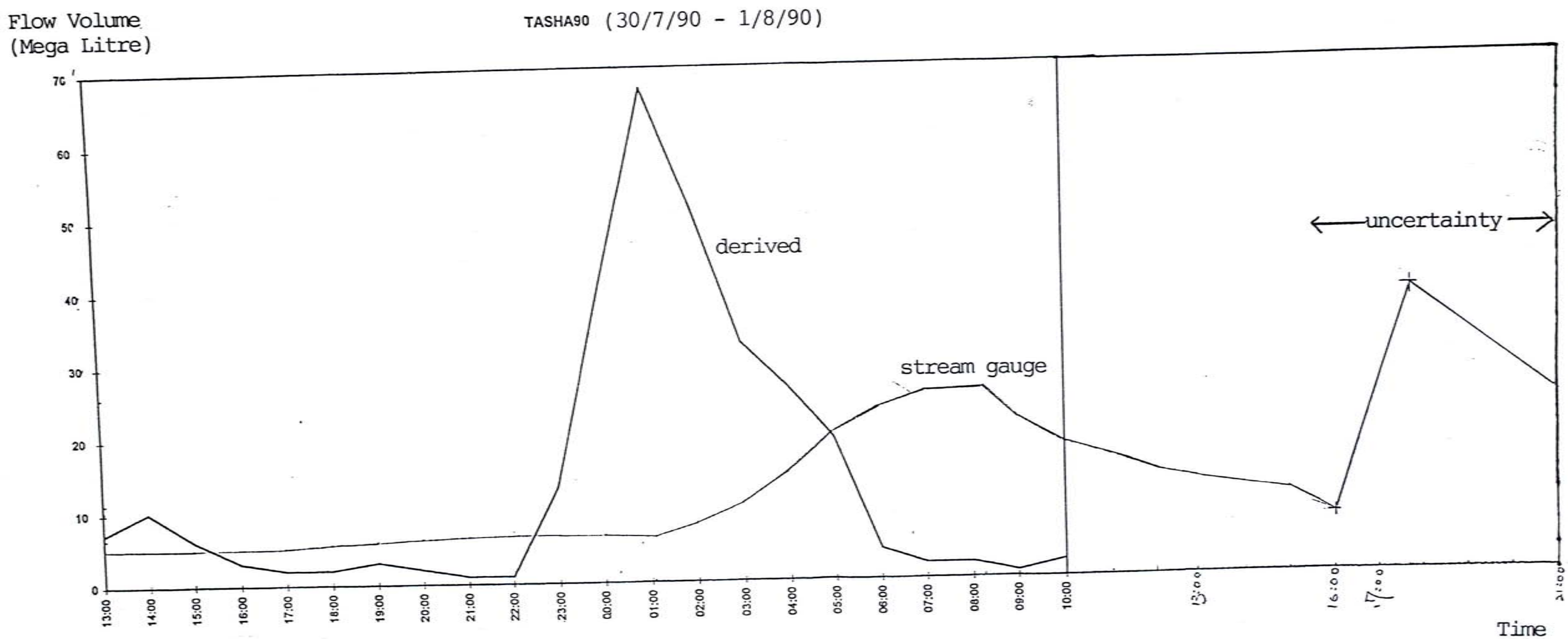



Figure 5.4 (Cont'd)

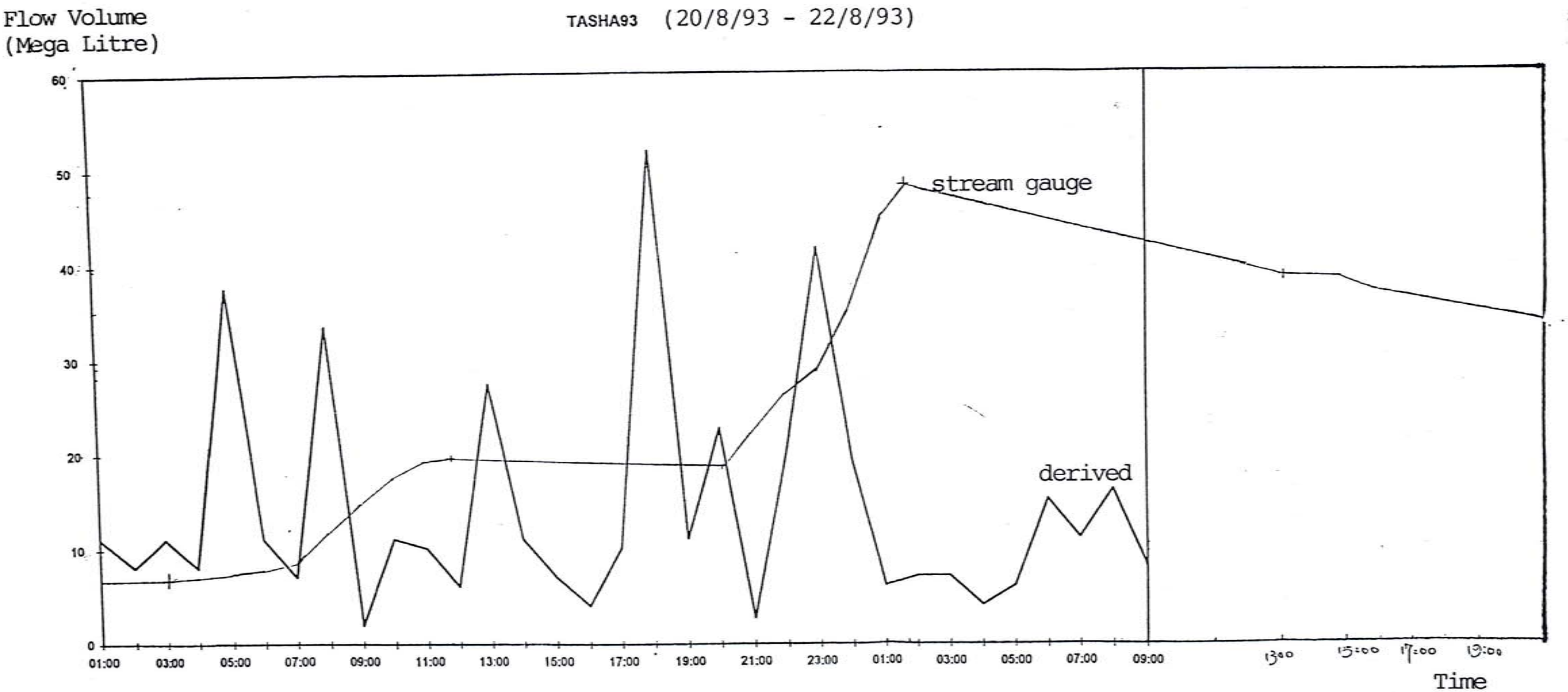
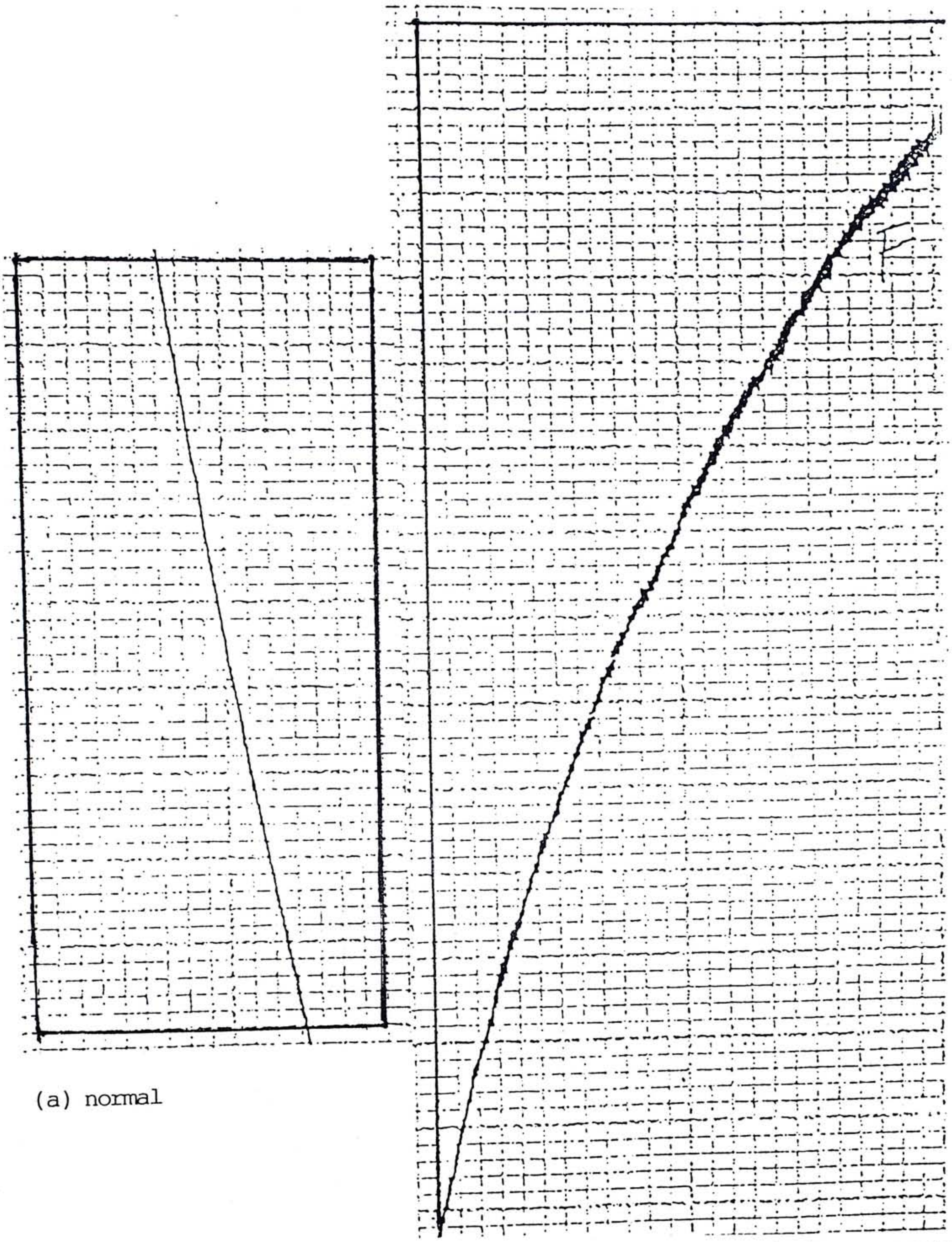



Figure 5.4 (Cont'd)



(a) normal

(b) faulty with thickened zig-zag curve

Figure 5.5 Instrumental error detected in hydrographs.

(Figure 5.4d), the two hydrographs are in fact quite close in shape with one peak except after 1600 hour on 31 July where another prominent rise occurs for stream gauge-generated hydrograph. But looking back to the original graph (Appendix E4), uncertainties or errors may occur in this part as indicated by the relatively thickened lines. Therefore if this time period is to be ignored, the overall shape of the two graphs corresponds quite well though with a large time lag of 7 hours.

Judging from the shape of hydrographs, it can be concluded that heavier storms like Brenda and Gordon result in a more similar pattern with the WSD data. This may be because in cases of more intense rains of longer duration, abstractive properties like infiltration, interception and subsurface flow become insignificant and might be ignored, resulting in the rainfall amount being directly proportional to overland flow. However, for less intense rains, the subsurface may not be immediately saturated or together with other parameters, varying abstraction rates occur with different time, all of which will affect the general shape of the hydrograph. The time lag between the time-area and WSD hydrographs, in which the former, for all cases, has resulted in earlier rises and falls may be explained by two reasons. First, the stream gauge is located at a much lower place than the 40 metre contour, thus requiring longer travel time to arrive at a peak. Second, this time is further increased by the fact that WSD hydrographs refer to stream flow through a collecting point compared to the total flow passing through the 40-metre contour line. The latter would require less distance and so less time for the first and subsequent peaks to start.

5.2.3.2 Flow Volume

As the Kam Tin catchment occupies about 60% of the total studied area (Table 5.2), it will be logical if flow volume is around 60% to 65% of the derived ones, considering the extension of area to lower land as well. In this aspect, less severe storms or those at times of lower rainfalls follow such patterns quite well (Figure 5.4c-e). This is especially reflected in Typhoon Nathan and the two Typhoon Tasha. However, for periods of very heavy and intensive falls, the amount is always underestimated when compared to the gauge records such as the latter half of Typhoon Brenda and Gordon. As previously mentioned, abstraction from surface flow may not be significant during this time and so the phi-index for the derivation of hydrographs here might all have reduced the estimated flow value.

Therefore, to obtain a better and more realistic picture of flow pattern, the phi-index is now used only for the start of the storm when abstraction still occurs. At times of peak flow, this index is totally erased, so a total of 11.91 mega litre (ie. 0.25mm x 39.7km x 12 x 0.1) is added to each flow record per hour. This was tried for both Typhoon Brenda and Gordon only (Figure 5.6) since these two storms had the better shape approximation but with peak flow volume far less than the stream gauge hydrographs. Results show that the two hydrographs now reach nearly the same value at the peak periods. As the Kam Tin catchment occupies about 60% of the total area, this means that there is a discrepancy of 40% flow volume. This is acceptable as the stream gauge collects water from a much wider area within the 0 and 40 metre elevation and no diversion of water usually occur in case of severe storm periods.

Considering the flow volumes of various storms, it can be deduced that the phi-index of 3 mm/h is more applicable to light rain and normal flow conditions. Owing to the steep terrain and shallow soil covering most Hong Kong slopes, the subsoil will quickly be saturated. In addition to the absence of large water-retention lakes or reservoirs, at least in this area, abstraction or diffusion of surface flow seems to become insignificant or can totally be ignored in periods of high rain

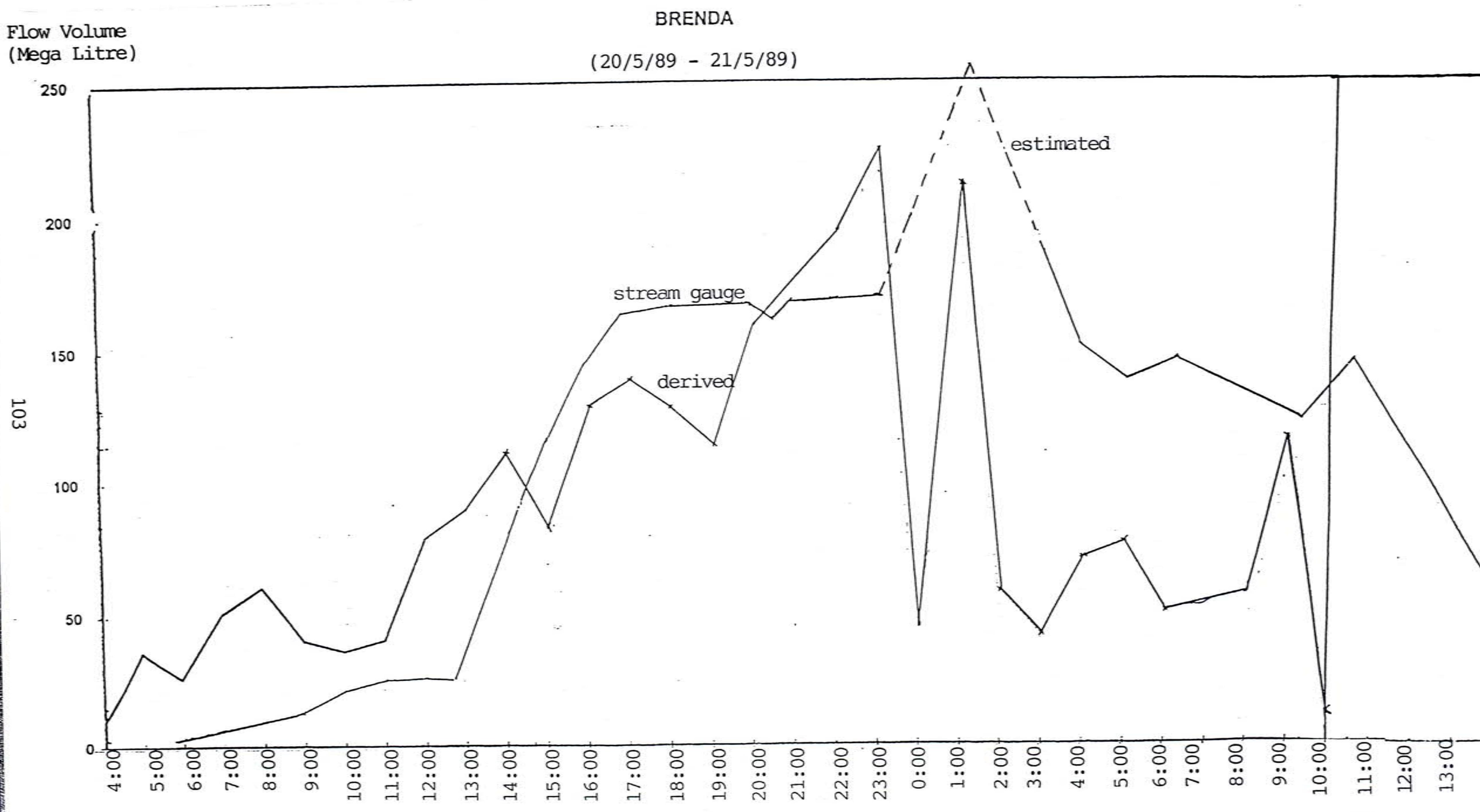



Figure 5.6 Modified hydrographs produced by time-area method.

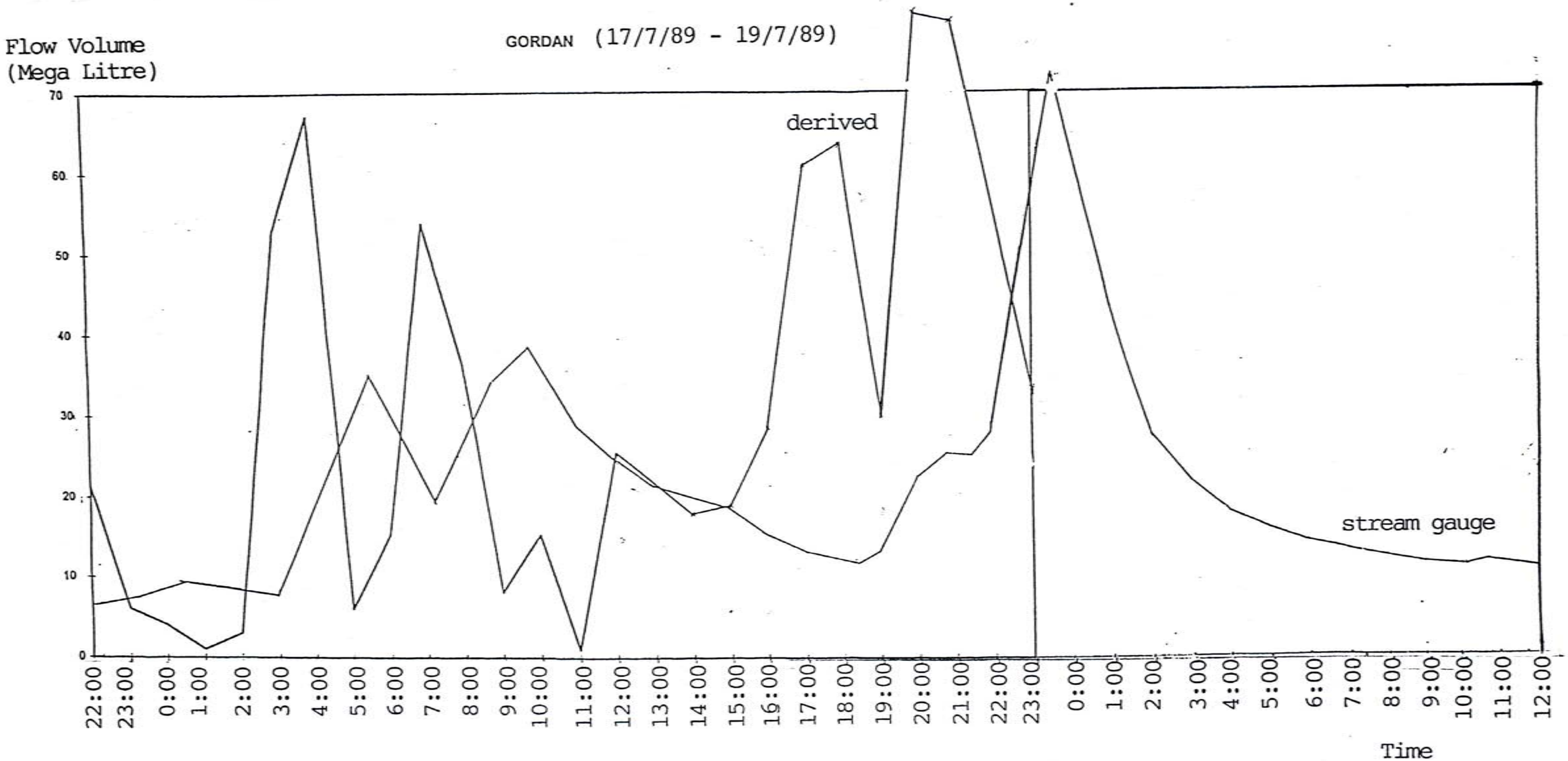



Figure 5.6 (Cont'd)

intensities. On the other hand, flow volumes derived from rain gauge data are more predictable for light than heavy rains. Uncertainties in the peak flow value are attributable not only to differing location of data collecting points, but also to one or more of the following - overestimation of flow for the stream gauge hydrographs as derived from the rating table in cases of high water levels, varying rain intensities over the region, contribution of domestic and industrial water and possible instrumentation errors or disruption especially during bad weather conditions. With more information at hand or previously-mentioned uncertainties solved, flow velocity could be estimated with greater accuracy and precision.

## 5.3 Spatio-Temporal Flow Pattern

Hydrographs discussed in the above sections refer to surface flow through a point or a line at different times of a storm only. Spatial pattern of flow at particular times could also be derived too from time-area tables (Appendix D) in the way indicated in Figure 5.7. This has only been produced for Typhoon Brenda from 1300 hour on 20$^{th}$ May to 900 hour on 21$^{st}$ May 1989 (Table 5.5), the period of peak surface flow and also the highest flow ever recorded in that stream gauge. Figures indicating

(a)

| Time | t0 | | t1 | | t2 | | t3 | | t4 | | t5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Effective rainfall (mm/5min) | | r1 | | r2 | | r3 | | r4 | | r5 | |

(b)

| Isochrone Value (min) | Area |
|---|---|
| 0-5 | A |
| 5-10 | B |
| 10-15 | C |
| 15-20 | D |
| 20-25 | E |
| 25-30 | F |

summation of value for each column will produce a spatial flow pattern for t3

(c)

| Time | t1 | t2 | t3 | t4 | t5 | t6 | t7 | t8 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| t1 | r1A | r1B | r1C | r1D | r1E | r1F | | | | |
| t2 | | r2A | r2B | r2C | r2D | r2E | r2F | | | |
| t3 | | | r3A | r3B | r3C | r3D | r3E | r3F | | |
| t4 | | | | r4A | r4B | r4C | r4D | r4E | r4F | |
| t5 | | | | | r5A | r5B | r5C | r5D | r5E | r5F |
| Sum of Flows (Km²-mm/5min) from different parts of the catchment at different times | | | | | | | | | | |

for the derivation of hydrographs at catchment outlet

Figure 5.7 Deriving (c) spatio-temporal flow pattern from (a) rainfall and (b) area information.

flow volume could of course be varied by different phi-index but the relative flow magnitude between different zone areas remain the same.

| Time | Flow Volume (Mega Litre) in Between Isochrones (min) 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 |
|---|---|---|---|---|---|---|
| 13:00 | 53.0935 | 24.411 | 12.074 | 7.1155 | 3.215 | 1.76 |
| 14:00 | 32.193 | 15.073 | 6.644 | 4.1415 | 2.0475 | 0.88 |
| 15:00 | 97.9445 | 45.137 | 20.748 | 10.8215 | 4.365 | 5.28 |
| 16:00 | 57.1495 | 25.493 | 13.38 | 5.402 | 3.5025 | 2.64 |
| 17:00 | 125.927 | 55.0565 | 25.483 | 11.4895 | 6.7 | 7.04 |
| 18:00 | 95.8825 | 42.926 | 20.145 | 9.59 | 5.8375 | 4.4 |
| 19:00 | 88.75 | 41.446 | 20.024 | 9.5435 | 5.55 | 3.52 |
| 20:00 | 78.532 | 36.016 | 17.05 | 8.376 | 4.67 | 3.52 |
| 21:00 | 123.754 | 57.243 | 27.946 | 12.5 | 9.3575 | 4.4 |
| 22:00 | 109.4295 | 49.8325 | 22.85 | 10.6935 | 9.07 | 3.52 |
| 23:00 | 144.5225 | 61.188 | 32.034 | 19.0115 | 7.885 | 5.28 |
| 0:00 | 79.0995 | 42.122 | 15.7615 | 7.4495 | 4.3825 | 2.64 |
| 1:00 | 144.0045 | 71.1295 | 31.097 | 16.6125 | 8.4775 | 4.4 |
| 2:00 | 49.1185 | 23.197 | 10.9065 | 6.2355 | 3.215 | 1.76 |
| 3:00 | 33.797 | 14.9595 | 7.5985 | 3.9005 | 1.455 | 1.76 |
| 4:00 | 52.4825 | 23.0835 | 11.861 | 5.9945 | 2.6225 | 2.64 |
| 5:00 | 83.827 | 38.018 | 17.143 | 8.951 | 6.43 | 3.52 |
| 6:00 | 29.343 | 13.671 | 6.672 | 3.613 | 0.575 | 1.76 |
| 7:00 | 34.038 | 15.552 | 6.7185 | 3.9005 | 1.455 | 1.76 |
| 8:00 | 21.308 | 10.764 | 4.2625 | 2.094 | 1.1675 | 0.885 |
| 9:00 | 91.5715 | 41.533 | 16.802 | 16.4905 | 4.975 | 1.76 |

Table 5.5 Spatio-temporal flow pattern of Typhoon Brenda at peak storm periods.

Assuming that no abstraction takes place here as discussed in section 5.2.3.2, it shows that spatially, the higher the land or greater the concentration time, the smaller will be the flow volume. This is logical since lower land usually covers a larger area and collects water from more widely-distributed tributaries. Hence, the extent to which flooding might occur depends very much on the one hand the configuration of the isochrone pattern, and on the other hand the channel size or capacity as to whether it could accomodate the flow volume at different times such as that in Table 5.5. Such channel geometry has not been studied here but from the flow maps produced here (Figure 5.8), flow is more concentrated within the southern catchments. Comparatively speaking, flooding may not be so serious in both Ngau Tam Mei and those parts towards the north. It therefore gives a general idea as to which parts of the basin need more attention and flood management.

Temporally speaking, the relative flow amount with time follows quite well with the hyetograph pattern (Figure 5.9) though with a time lag. However, this assumes that the surface flow is drained away continuously and effectively. If either the natural or artificial drainage system is blocked, such a flow will be accumulated for subsequent hours, causing severe flooding. Unfortunately, this has become the common scenario in recent years in which stream channels are often blocked by rubbish, uncut wild grass and silted by dumpings from nearby constructions or illegal reclamation of farmland and fish ponds.

In summary, the time-area method provides a simple and direct means of routing surface runoff basically on the natural terrain. The parameters

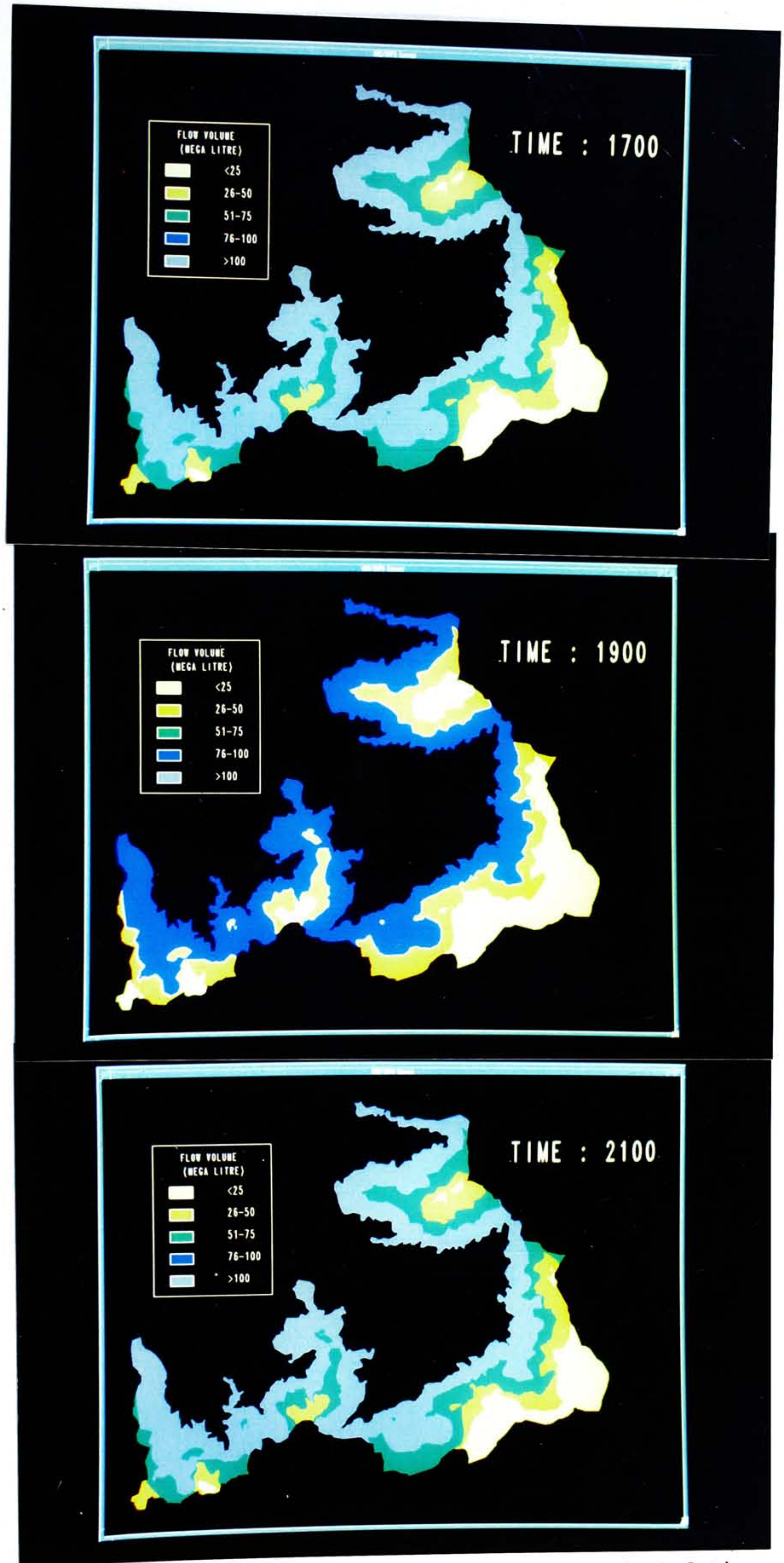



Figure 5.8 Flow maps of Typhoon Brenda at selected times.

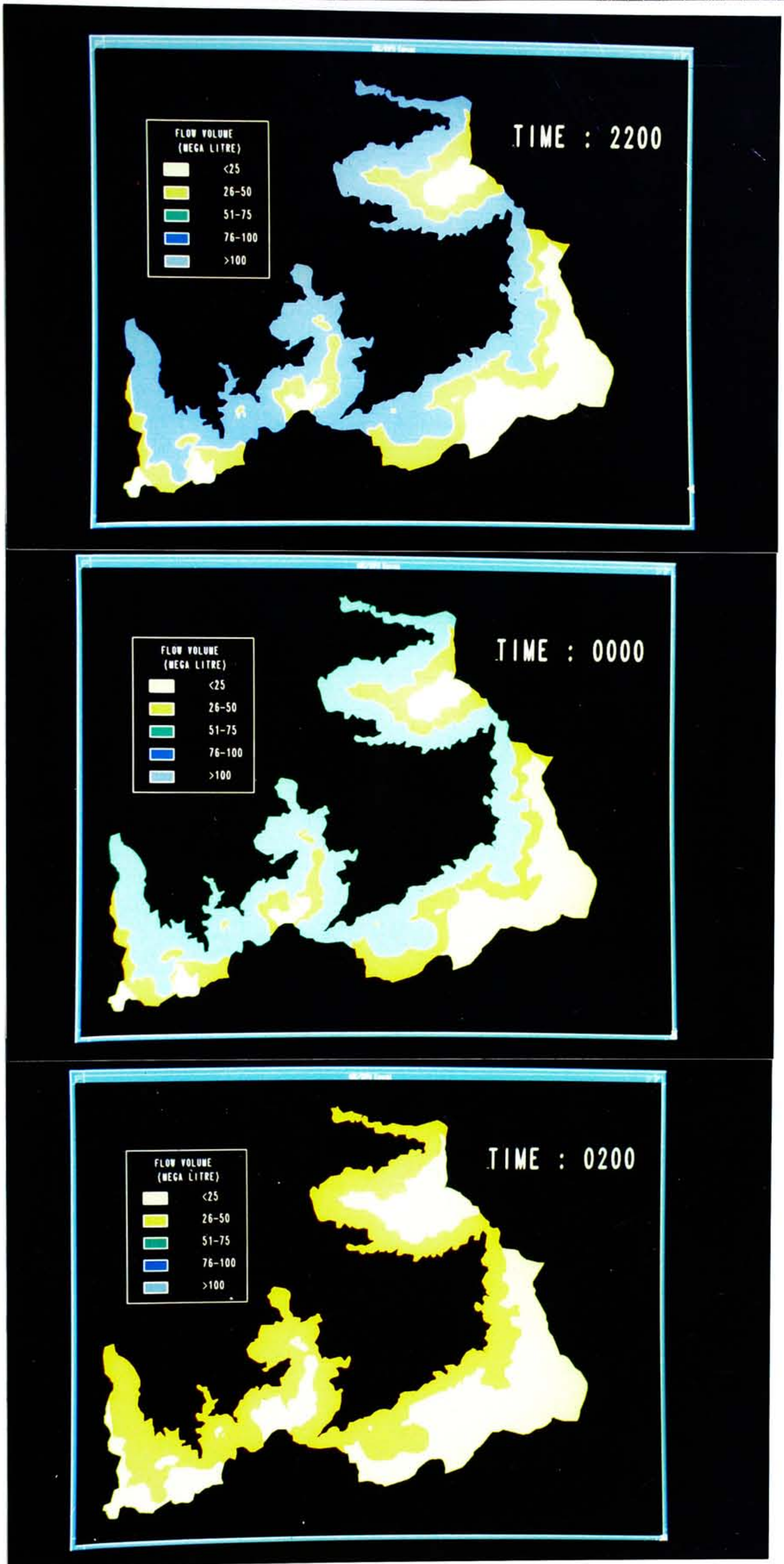



Figure 5. 8 (Cont'd)

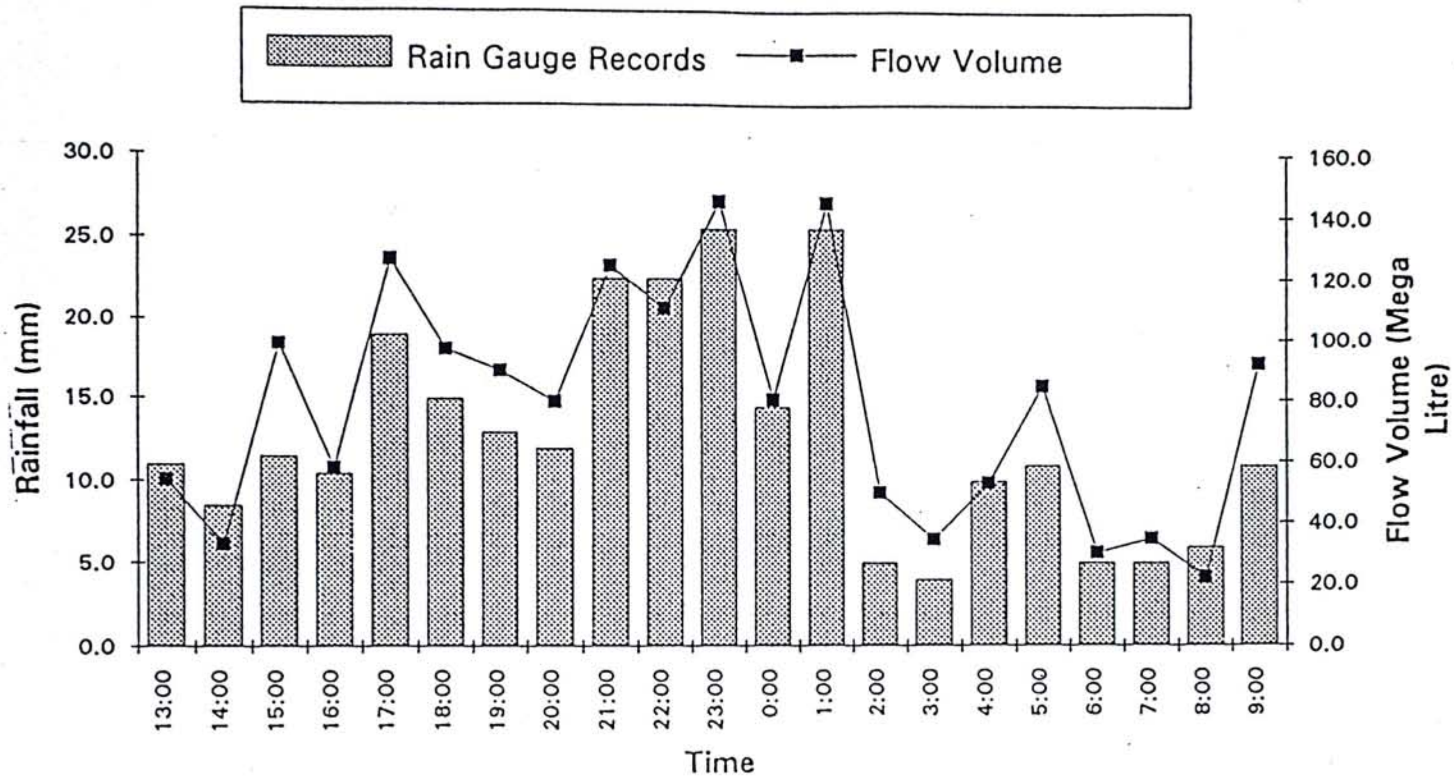



Figure 5.9 Hyetograph showing rain gauge records and flow volume of Typhoon Brenda.

needed, like slope and streamlength are usually obtainable from diverse sources - maps, aerial photographs or survey data. The model is more appropriate for heavy storms when abstraction or diffusion become constant or negligible and for upland areas where human intervention in affecting the surface flow is the least.

□

# CHAPTER 6 CONCLUSION

## 6.1 Achievements of the Study

The merits of geographic information system lies in its advanced capabilities for manipulating both spatial and aspatial information and analyzing their relationships. And spatial analysis functions can be combined to provide an almost unlimited variety of analysis and modelling capabilities. In this study, the Arc/Info together with other related database software have been useful in terrain modelling, networking streamflow and routing a spatio-temporal pattern of surface runoff. This would otherwise be impossible for an intensive and detailed study involving voluminous data and calculations.

Achievements in this study can therefore be summarized into three main aspects. First and the most fundamental of all, a very detailed digital topographic base is built, consisting of a digital elevation model, streamlength, stream channel slope and even land uses. From this, other parameters like aspect, contours of any defined vertical interval, hypsometric coloring and hill shading can be derived conveniently and quickly if required in any applications. In other words, such data base is useful not only for hydrological modelling, but also for any other studies related to terrain characteristics. Second, routing of stream surface flow in small catchments has proved to be possible with simple and easily available hydrological variables like drainage area and continuous rainfall records. With an appropriate and adjustable abstraction index, this can avoid the complicated computations involved in hydraulic modelling. Third, by putting the northwest New Territories as the study area, spatio-temporal flow pattern of the uplands just adjacent to the most flood prone lowlands of Hong Kong can be observed clearly, thus providing valuable information for carrying out large and expensive projects related to flood prevention and basin management.

## 6.2 Evaluation of the Applicability of Geographic Information System

In spite of the above-mentioned achievements, there are still rooms for improvement for even better and more accurate results. In the first place, the claimed powerful and magnificient capabilities of geographic information system can only be so if the data collected, entered, stored and processed are sufficiently reliable and error-free for the purposes for which they are required (Burrough, 1986). Take this study as an example, point data of spot heights are input into the Arc/Info system essentially in vector format. The TIN model built and thereby interpolation and contouring are based primarily on the Delauney

Triangulated Method and linear or bivariate quintic interpolation. Such techniques of manipulating DEM data are proved to be capable of achieving a high level of accuracy in many studies provided that there are sufficiently dense and critical point height information. Nevertheless, in terms of input speed, unless digital terrain information is already available, manual digitization of even only points is tremendously time-consuming. Undoubtedly, this could be improved with faster input devices like automatic line followers or optical scanners, in which case not only spot heights are considered, but also contours can be incorporated into the Digital Terrain Modelling. In this way, more subtle change of landscape, especially of slope and more accurate delineation of the 40-metre contour as study boundary could be obtained before any runoff modelling is performed. Also, streams and their confluences between tributaries could be input directly without having to link up points. Although it is commonly agreed that consistent and updated information are although of utmost importance for any mapping or research, map sheets, the prime information source used here are edited or revised in different years. Some, in particular the remote highlands, are not revised for more than 10 years! In addition to some parts where terrain information is totally unknown, eg. those covered by thick bushes and are inaccesible for surveyors, inconsistencies in data sources inevitably occur but still have to be relied on.

In data processing, stream channel slopes, surfacelength, concentration time of each stream segment could be derived both efficiently and accurately by vector algorithms inherent in the Arc/Info system. However, in determining flow direction for the derivation of cumulative concentration time and thereafter interpolating isochrones, much time have to be put on identifying height differences between different sets of points along a stream before routing can take place using the networking commands interactively. This is of course not the best method in view of the larger volume of data. With suitable software which handle hydrologic parameters like flow direction, greater efficiency can be achieved but again these are often raster-based instead of vector-based processing techniques.

All in all, with more consistent and reliable information sources, more efficient data capture devices and more accurate data processing or algorithms or packages suitable for a particular area of study, the geographic information system could manifest its unlimited applications on the study more speedily and even extend that to other areas, at least in providing a topographic base detailed enough for further applications or spatial analyses.

## 6.3 Evaluation of the Hydrological Model

The basic rationale of the model in this study is that rainfall data are used to estimate and route surface flow pattern directly without the need to obtain streamflow data. This can be an advantage since in reality in many places, there are more rain gauges than stream gauges. Also, rainfall data obtained are often more reliable and detailed. Therefore, if more rain gauges are found within the studied area like those installed on northern part of Hong Kong Island or the urban Kowloon, spatial and temporal variation of rain intensity could be incorporated into the model, resulting in more accurate prediction of flow. But unfortunately this is one of the most serious limitations in this study, in which point rainfall depth has to be assumed for the whole catchment.

Similarly, little information is available for local abstraction or diffusion of surface flow. Although this study has shown that such values may be neglected for steep upland areas and for large storms soon as it starts, the derivation of local phi-indices is still valuable for other hydrological studies. In small places like Hong Kong where land use is not so diverse, a few appropriate phi-indices - maybe one for urban area, grassland and woodland separately, will be sufficient and of course this requires more empirical studies. With just these two hydro-data - rainfall and abstraction index, the surface runoff can be routed by the simple principles of Time-Area Method. In spite of the inavailability of a complete and consistent set of data which often appears in any research, results from this study show that the shapes of the derived hydrographs do not deviate significantly from real conditions. It can be concluded that point rainfall data and a constant infiltration parameter could be suitably applied for all other small catchments in Hong Kong too, provided that a detailed topographic base is available for the derivation of concentration time which is central to this studied method. In fact, this poses no great difficulty to almost any parts of the territory since topographic information from either large-scale maps or aerial photographs are often well-documented, quite a dense network of automatic rain gauges is found within the whole of Hong Kong and very diverse land uses are usually uncommon in catchment areas.

## 6.4 Conclusion

On the condition that the Time-Area Method is justified, it is always true that better and non-defective instrumentations, more intensive and frequent topographic surveying and so forth will lead to far more reliable information source and better approximation of the model to actual condition. With such simulated results, the prediction of flood magnitude in relation to forecasted rainfall magnitude (eg. 1 in 10, 1 in 50 or 1 in 100 years storms) becomes extremely useful for planning and designing structures to combat flooding. The spatial pattern derived gives also valuable information to areas where more attention and constructions should be made, thus achieving a higher cost-effective economy in the whole flood or basin management scheme.

□

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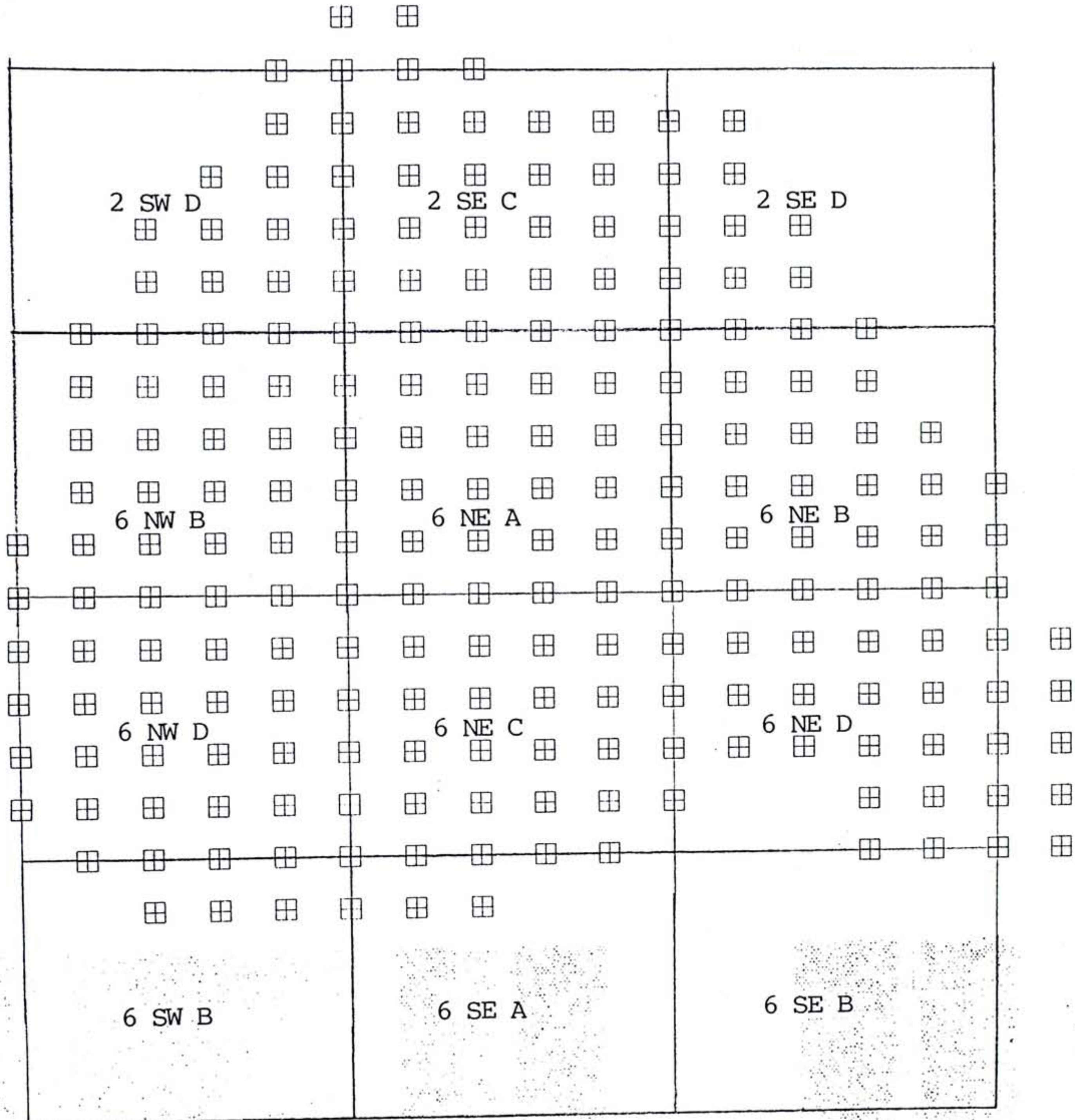
□

# APPENDIX A




Digitized 1:1000 map sheets are marked by the tics at the 4 corners whereas blank areas are supplemented by digitizing 1:5000 map sheets.

## APPENDIX B

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

void conv(FILE *inf, FILE *outf);
void create(FILE *outf, double x, double y, int n, int m);
void append(FILE *outf, double x, double y);
long f_pointer;

main(int argc, char *argv[])
{
      char filename1[20],filename2[20];
      FILE *inf;
      FILE *outf;

      if ( argc<2){
         printf("Please enter the input filename : ");
         gets(filename1);
      }
      else{
         strcpy(filename1,argv[1]);
      }

      if ( argc<3){
         printf("Please enter the output filename : ");
         gets(filename2);
      }
      else{
         strcpy(filename2,argv[2]);
      }

      if ((inf=fopen(filename1,"r"))==NULL)
      {
          printf("Conversion Complete!");
          exit(1);
      }

      outf=fopen(filename2,"w");

      conv(inf,outf);

      fclose(inf);
      fclose(outf);
}

void conv(FILE *inf, FILE *outf)
{
      char test[5];
      char a1[15],a2[15],a3[15],a4[15],a5[15];
      char b1[15],b2[15],b3[15],b4[15],b5[15];
      char c[15];
      double x,y;
      int m;
      long i, k, temp1=0, temp2=0;
      int j, n=0, test_value;
```

```
        fprintf(outf," 0\nSECTION\n  2\nENTITIES\n  0\n");

        for(;;)
        {
            if(feof(inf))break;
            fscanf(inf,"%s",test);
            test_value=strcmp(test,"TEXT");
        if (!test_value)
        {
            fscanf(inf,"%s%s%s%s%s%lf%s%lf%s%s%s%s%s%ld",
            a1,a2,a3,a4,a5,&x,c,&y,b1,b2,b3,b4,b5,&i);
            j=i%1000;
            k=j/100;

            if(k){
                    temp2=i;
                    if(abs((temp1-temp2))==1){
                        append(outf,x,y);
                        m=1;
                    }
                    else{
                        create(outf,x,y,n,m);
                        m=0;
                        n=1;
                    };
                    temp1=i;
            }
        }
    }
    fprintf(outf,"SEQEND\n  8\n0\n  0\n");
    fprintf(outf,"ENDSEC\n  0\nEOF");
}

void append(FILE *outf, double x, double y)
{
    fprintf(outf,"VERTEX\n  8\n0\n");
    fprintf(outf," 10\n%15.6f\n 20\n%15.6f\n 30\n0.0\n0\n",x,y);
}

void create(FILE *outf, double x, double y, int n, int m)
{
    int c;
    long d;
    long a=10,b;
    d=f_pointer-131;

    if(!m){
        c=fseek(outf,d,SEEK_SET);
    };
    if(n){
        fprintf(outf,"SEQEND\n  8\n0\n  0\n");
    };
    fprintf(outf,"POLYLINE\n  8\n0\n 66\n      1\n  0\n");
    fprintf(outf,"VERTEX\n  8\n0\n");
    fprintf(outf," 10\n%15.6f\n 20\n%15.6f\n 30\n0.0\n0\n",x,y);
    f_pointer=ftell(outf);
}
```

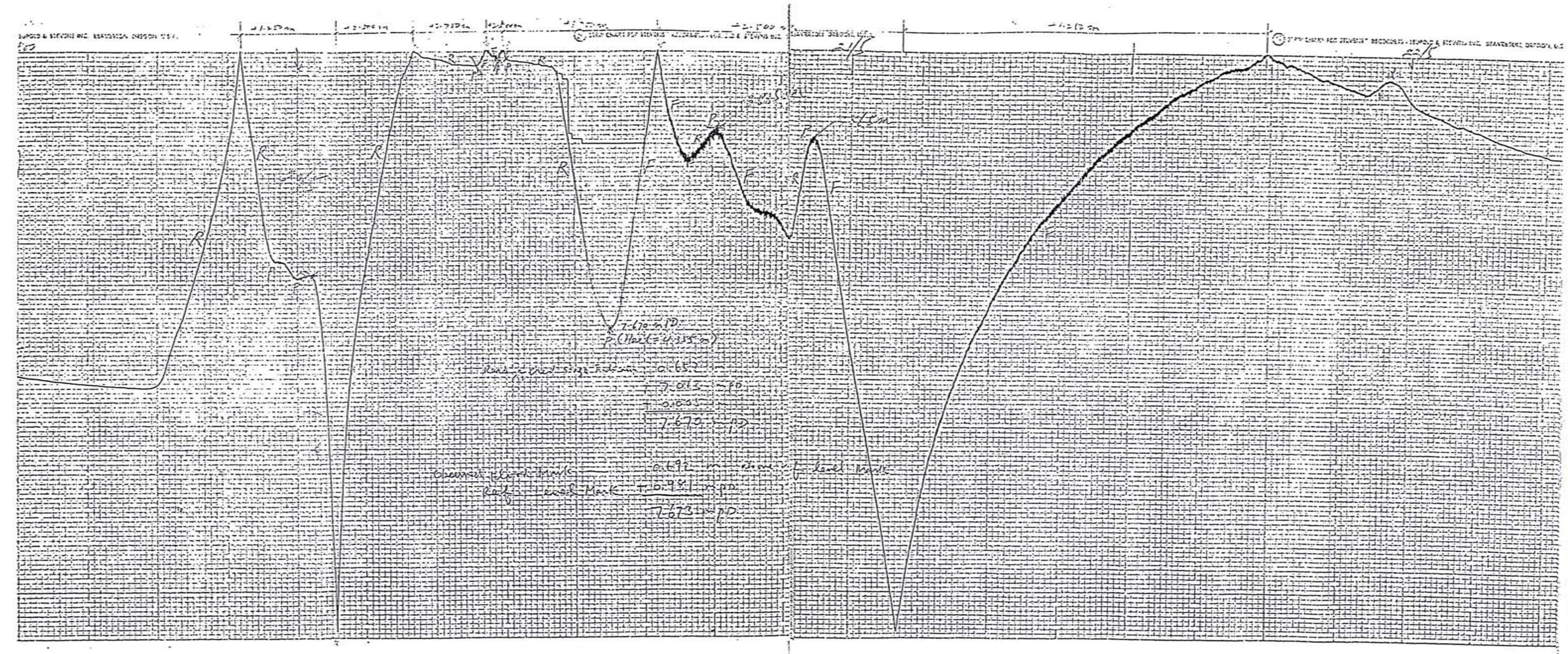
# APPENDIX C

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Special Projects Division Geotechnical Engineering Office | | | | | | | |
| Civil Engineering Department | | | | | | | |
| Brenda | | | | | | | |
| 20/5/89 3:25 to 21/5/89 9:15 (selected rainfall records) | | | | | | | |
| | | | | | | | |
| 03:25 | 0.5 | | 06:20 | 0.5 | | 09:15 | 1 |
| 03:30 | 0 | | 06:25 | 0 | | 09:20 | 1 |
| 03:35 | 0.5 | | 06:30 | 0 | | 09:25 | 0.5 |
| 03:40 | 0 | | 06:35 | 0 | | 09:30 | 1 |
| 03:45 | 0.5 | | 06:40 | 0 | | 09:35 | 1 |
| 03:50 | 0 | | 06:45 | 0.5 | | 09:40 | 1 |
| 03:55 | 0 | | 06:50 | 1 | | 09:45 | 1 |
| 04:00 | 0.5 | | 06:55 | 1 | | 09:50 | 0.5 |
| 04:05 | 0 | | 07:00 | 1 | | 09:55 | 1.5 |
| 04:10 | 0 | | 07:05 | 0.5 | | 10:00 | 0.5 |
| 04:15 | 0.5 | | 07:10 | 1 | | 10:05 | 0.5 |
| 04:20 | 0 | | 07:15 | 1 | | 10:10 | 1 |
| 04:25 | 0.5 | | 07:20 | 1 | | 10:15 | 0.5 |
| 04:30 | 0 | | 07:25 | 1 | | 10:20 | 0.5 |
| 04:35 | 0.5 | | 07:30 | 1 | | 10:25 | 0 |
| 04:40 | 0 | | 07:35 | 1.5 | | 10:30 | 0.5 |
| 04:45 | 0.5 | | 07:40 | 1.5 | | 10:35 | 1 |
| 04:50 | 0.5 | | 07:45 | 1 | | 10:40 | 1.5 |
| 04:55 | 0.5 | | 07:50 | 1 | | 10:45 | 1 |
| 05:00 | 0.5 | | 07:55 | 2 | | 10:50 | 1 |
| 05:05 | 0.5 | | 08:00 | 1.5 | | 10:55 | 1 |
| 05:10 | 0.5 | | 08:05 | 1 | | 11:00 | 0 |
| 05:15 | 1 | | 08:10 | 0.5 | | 11:05 | 0.5 |
| 05:20 | 1 | | 08:15 | 0.5 | | 11:10 | 0.5 |
| 05:25 | 1 | | 08:20 | 1 | | 11:15 | 1 |
| 05:30 | 1 | | 08:25 | 1.5 | | 11:20 | 1.5 |
| 05:35 | 1 | | 08:30 | 2 | | 11:25 | 1 |
| 05:40 | 0.5 | | 08:35 | 2 | | 11:30 | 0.5 |
| 05:45 | 1 | | 08:40 | 1 | | 11:35 | 1 |
| 05:50 | 0.5 | | 08:45 | 1 | | 11:40 | 1 |
| 05:55 | 1 | | 08:50 | 1 | | 11:45 | 1 |
| 06:00 | 1 | | 08:55 | 0.5 | | 11:50 | 1.5 |
| 06:05 | 1.5 | | 09:00 | 1 | | 11:55 | 2 |
| 06:10 | 0.5 | | 09:05 | 0.5 | | 12:00 | 2 |
| 06:15 | 1 | | 09:10 | 0.5 | | 12:05 | 2 |

# APPENDIX D

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2.64 | | | | | | | | | | | | | | | | | | |
| | 2.5875 | 7.92 | | | | | | | | | | | | | | | | | |
| | 2.7795 | 0.8625 | 2.64 | | | | | | | | | | | | | | | | |
| | 10.8425 | 4.6325 | 1.4375 | 4.4 | | | | | | | | | | | | | | | |
| | 23.7075 | 10.8425 | 4.6325 | 1.4375 | 4.4 | | | | | | | | | | | | | | |
| | 86.792 | 37.932 | 17.348 | 7.412 | 2.3 | 7.04 | | | | | | | | | | | | | |
| | | 141.037 | 61.6395 | 28.1905 | 12.0445 | 3.7375 | 11.44 | | | | | | | | | | | | |
| | | | 151.886 | 66.381 | 30.359 | 12.971 | 4.025 | 12.32 | | | | | | | | | | | |
| | | | | 206.131 | 90.0885 | 41.2015 | 17.6035 | 5.4625 | 16.72 | | | | | | | | | | |
| | | | | | 119.339 | 52.1565 | 23.8535 | 10.1915 | 3.1625 | 9.68 | | | | | | | | | |
| | | | | | | 119.339 | 52.1565 | 23.8535 | 10.1915 | 3.1625 | 9.68 | | | | | | | | |
| | | | | | | | 86.792 | 37.932 | 17.348 | 7.412 | 2.3 | 7.04 | | | | | | | |
| | | | | | | | | 54.245 | 23.7075 | 10.8425 | 4.6325 | 1.4375 | 4.4 | | | | | | |
| | | | | | | | | | 32.547 | 14.2245 | 6.5055 | 2.7795 | 0.8625 | 2.64 | | | | | |
| | | | | | | | | | | 54.245 | 23.7075 | 10.8425 | 4.6325 | 1.4375 | 4.4 | | | | |
| | | | | | | | | | | | 10.849 | 4.7415 | 2.1685 | 0.9265 | 0.2875 | 0.88 | | | |
| | | | | | | | | | | | | 10.849 | 4.7415 | 2.1685 | 0.9265 | 0.2875 | 0.88 | | |
| | | | | | | | | | | | | | 10.849 | 4.7415 | 2.1685 | 0.9265 | 0.2875 | 0.88 | |
| | | | | | | | | | | | | | | 21.698 | 9.483 | 4.337 | 1.853 | 0.575 | 1.76 |
| | | | | | | | | | | | | | | | 10.849 | 4.7415 | 2.1685 | 0.9265 | 0.2875 |
| | | | | | | | | | | | | | | | | 32.547 | 14.2245 | 6.5055 | 2.7795 |
| | | | | | | | | | | | | | | | | | 32.547 | 14.2245 | 6.5055 |
| | | | | | | | | | | | | | | | | | | 43.396 | 18.966 |
| | | | | | | | | | | | | | | | | | | | 32.547 |
| SUM2 | 129.349 | 203.227 | 239.584 | 313.952 | 258.531 | 236.446 | 195.871 | 144.005 | 103.677 | 99.5665 | 57.6745 | 37.69 | 27.654 | 33.612 | 28.1145 | 43.7195 | 51.9605 | 66.5075 | 62.8455 |

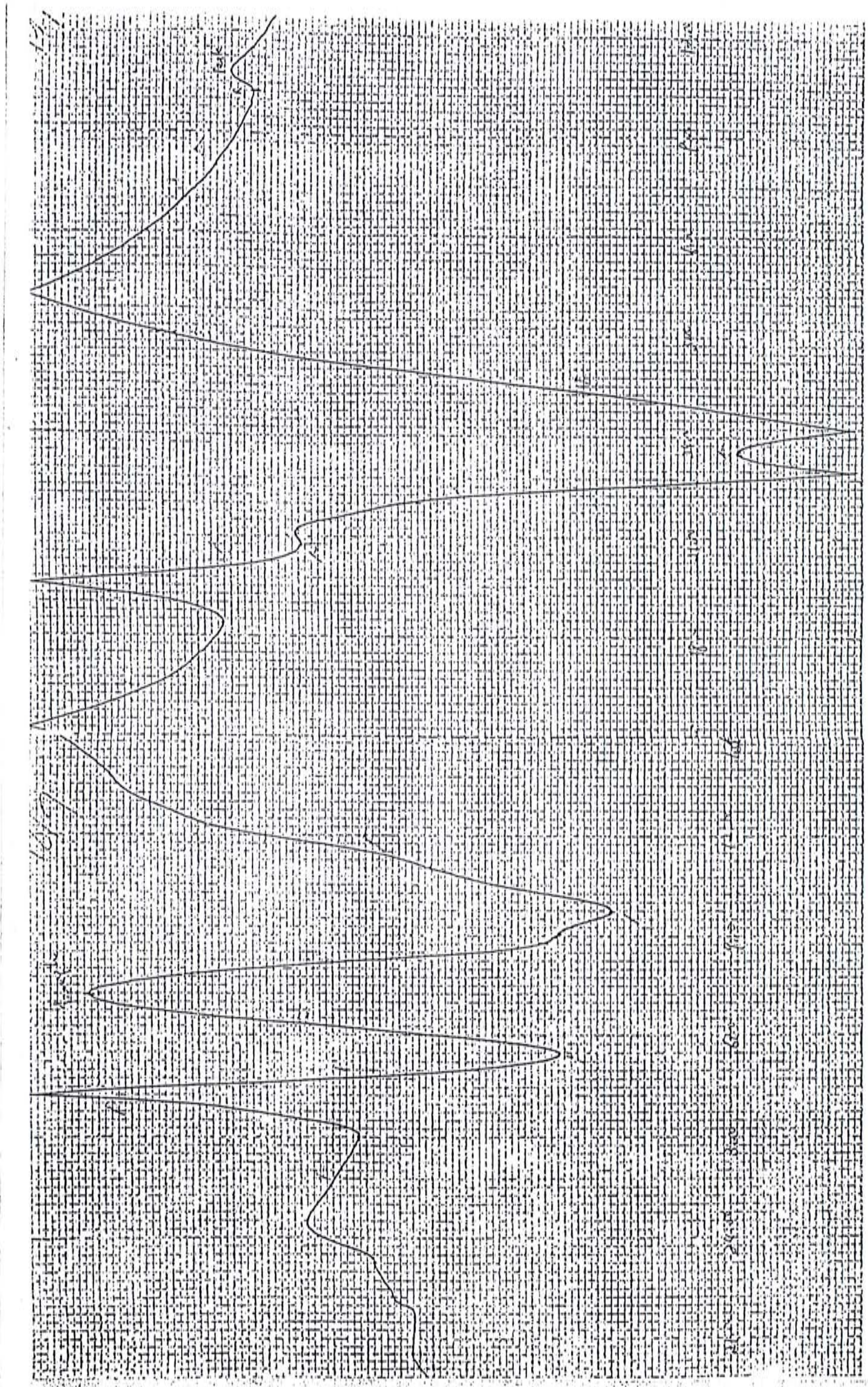
## APPENDIX E-1



BRENDA

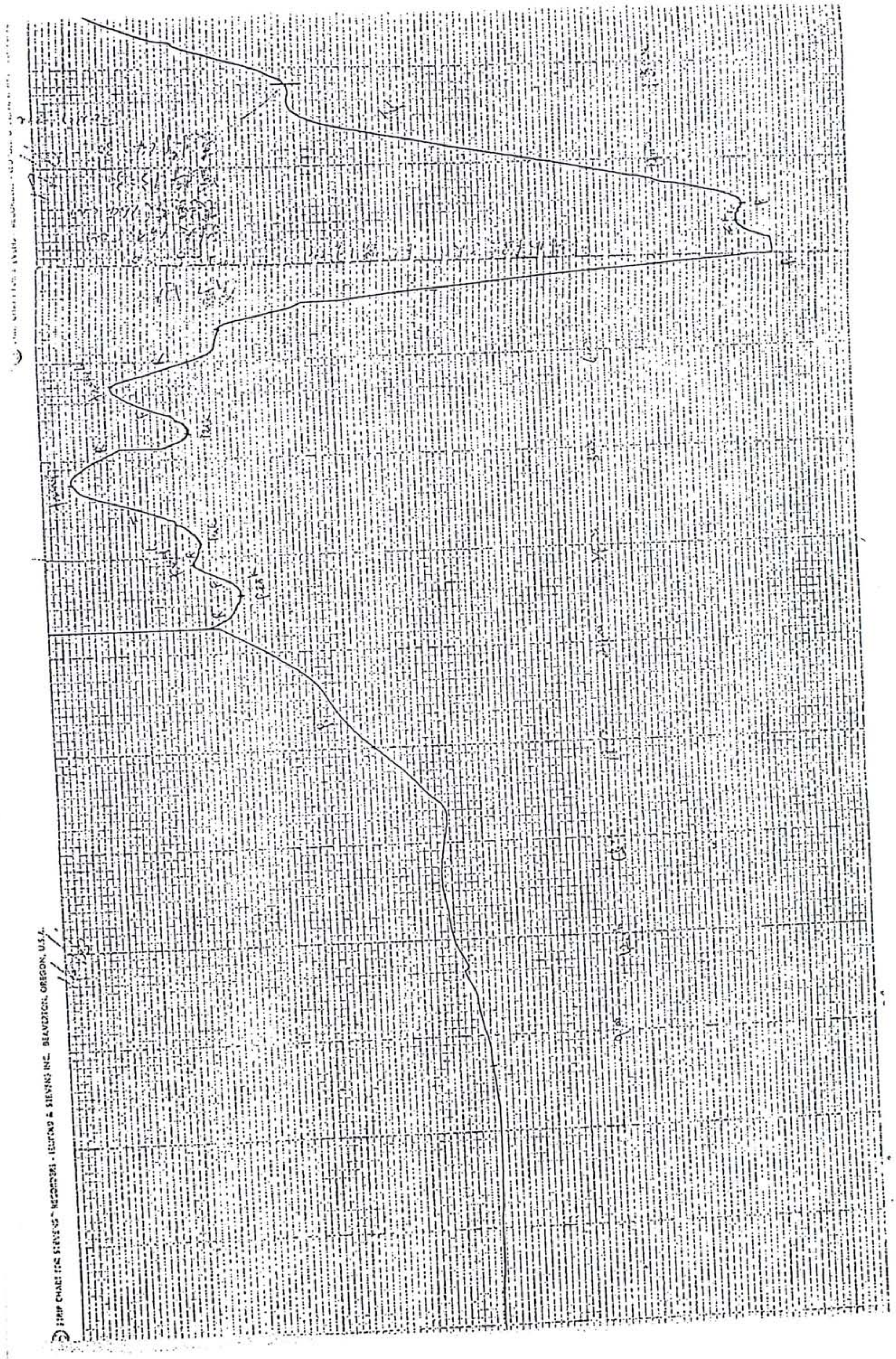
Source : Water Services Department

## APPENDIX E-2



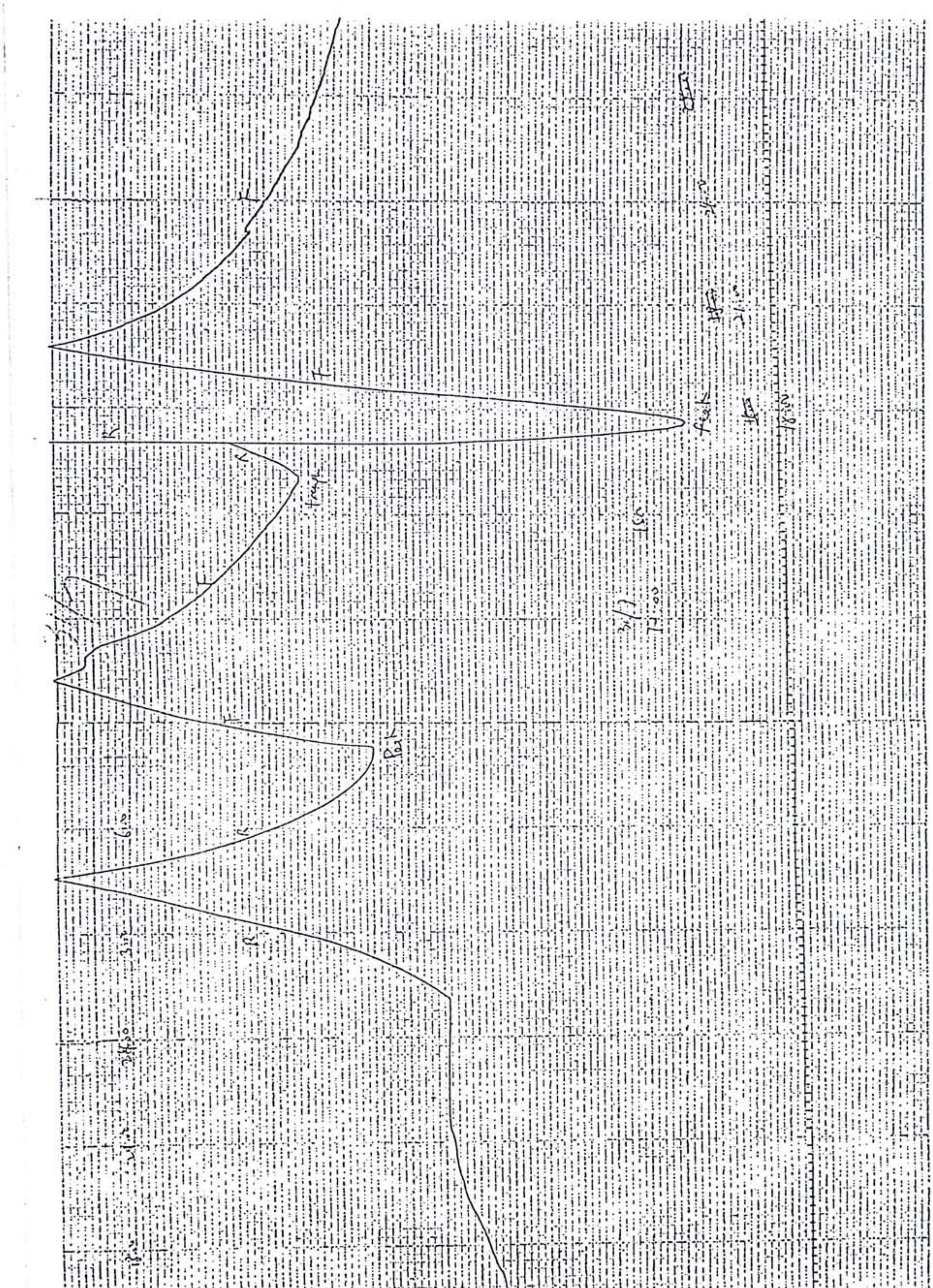
GORDON

# APPENDIX E-3



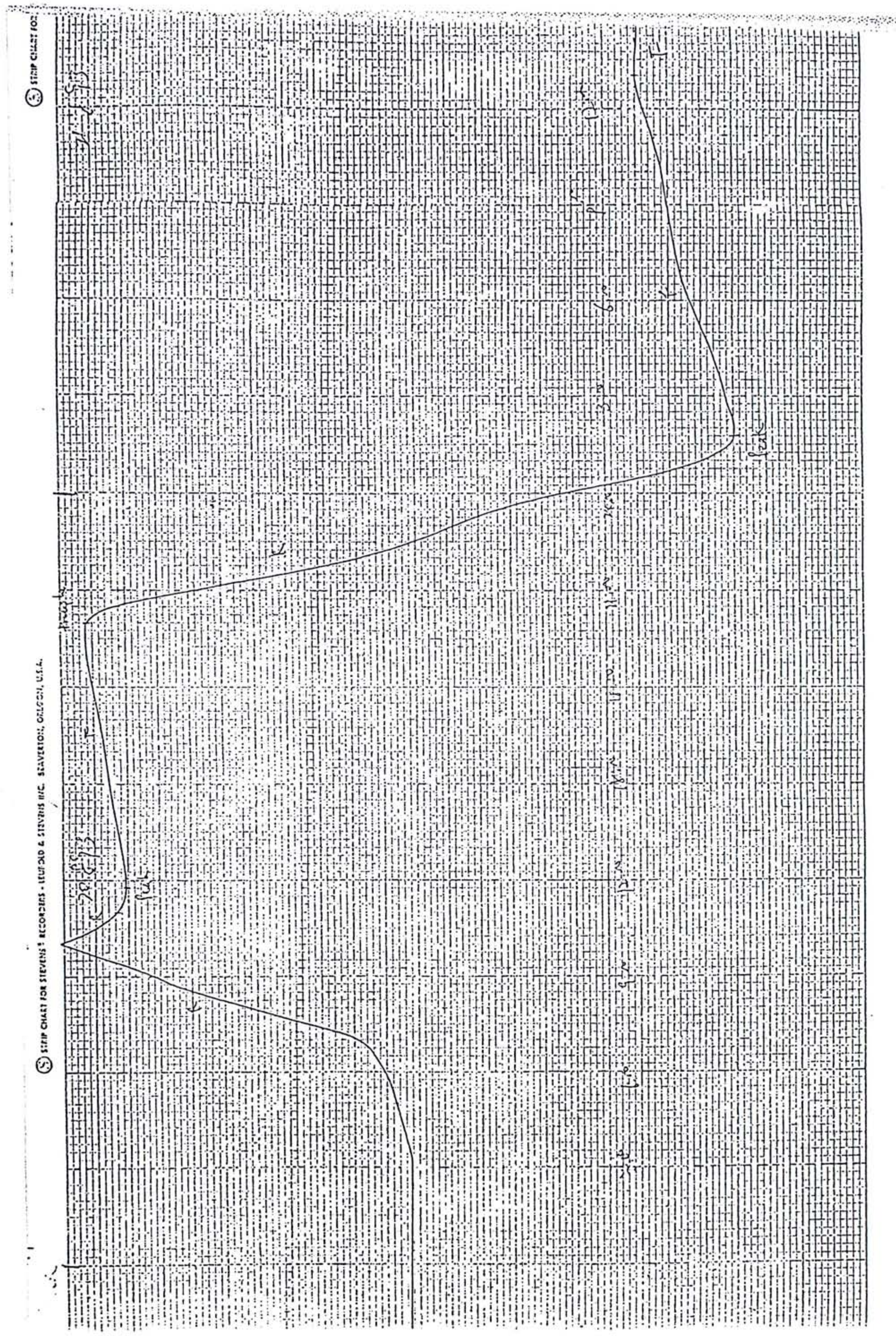
NATHAN

## APPENDIX E-4



TASHA (1990)

# APPENDIX E-5



TASHA (1993)

# APPENDIX F

HYDROLOGICAL SURVEYS

DATE:- 24 APR 1992 RATING TABLE NO. 11 FOR STATION NO. 11 KAM TIN

PAGE 13 OF 14

| HEAD M | 0.000 MLD | 0.001 MLD | 0.002 MLD | 0.003 MLD | 0.004 MLD | 0.005 MLD | 0.006 MLD | 0.007 MLD | 0.008 MLD | 0.009 MLD | HEAD M |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.60 | 3581.0792 | 3583.5959 | 3586.1138 | 3588.6327 | 3591.1527 | 3593.6738 | 3596.1959 | 3598.7191 | 3601.2434 | 3603.7687 | 3.60 |
| 3.61 | 3606.2952 | 3608.8226 | 3611.3512 | 3613.8808 | 3616.4115 | 3618.9433 | 3621.4761 | 3624.0101 | 3626.5450 | 3629.0811 | 3.61 |
| 3.62 | 3631.6182 | 3634.1564 | 3636.6957 | 3639.2361 | 3641.7775 | 3644.3200 | 3646.8635 | 3649.4082 | 3651.9539 | 3654.5007 | 3.62 |
| 3.63 | 3657.0485 | 3659.5975 | 3662.1475 | 3664.6986 | 3667.2507 | 3669.8039 | 3672.3582 | 3674.9136 | 3677.4701 | 3680.0276 | 3.63 |
| 3.64 | 3682.5862 | 3685.1459 | 3687.7066 | 3690.2685 | 3692.8314 | 3695.3954 | 3697.9604 | 3700.5266 | 3703.0938 | 3705.6621 | 3.64 |
| 3.65 | 3708.2314 | 3710.8019 | 3713.3734 | 3715.9460 | 3718.5197 | 3721.0944 | 3723.6702 | 3726.2471 | 3728.8339 | 3731.4349 | 3.65 |
| 3.66 | 3734.0371 | 3736.6403 | 3739.2447 | 3741.8501 | 3744.4566 | 3747.0643 | 3749.6731 | 3752.2829 | 3754.8939 | 3757.5059 | 3.66 |
| 3.67 | 3760.1191 | 3762.7334 | 3765.3488 | 3767.9653 | 3770.5829 | 3773.2016 | 3775.8214 | 3778.4423 | 3781.0643 | 3783.6874 | 3.67 |
| 3.68 | 3786.3116 | 3788.9370 | 3791.5634 | 3794.1910 | 3796.8196 | 3799.4494 | 3802.0802 | 3804.7122 | 3807.3453 | 3809.9795 | 3.68 |
| 3.69 | 3812.6148 | 3815.2512 | 3817.8887 | 3820.5273 | 3823.1671 | 3825.8079 | 3828.4498 | 3831.0929 | 3833.7371 | 3836.3823 | 3.69 |
| 3.70 | 3839.0287 | 3841.6762 | 3844.3248 | 3846.9745 | 3849.6254 | 3852.2773 | 3854.9303 | 3857.5845 | 3860.2398 | 3862.8961 | 3.70 |
| 3.71 | 3865.5536 | 3868.2122 | 3870.8719 | 3873.5328 | 3876.1947 | 3878.8578 | 3881.5219 | 3884.1872 | 3886.8536 | 3889.5211 | 3.71 |
| 3.72 | 3892.1897 | 3894.8594 | 3897.5302 | 3900.2022 | 3902.8752 | 3905.5494 | 3908.2247 | 3910.9011 | 3913.5786 | 3916.2573 | 3.72 |
| 3.73 | 3918.9370 | 3921.6179 | 3924.2998 | 3926.9829 | 3929.6671 | 3932.3525 | 3935.0389 | 3937.7264 | 3940.4151 | 3943.1049 | 3.73 |
| 3.74 | 3945.7958 | 3948.4878 | 3951.1309 | 3953.8752 | 3956.5705 | 3959.2670 | 3961.9646 | 3964.6633 | 3967.3632 | 3970.0641 | 3.74 |
| 3.75 | 3972.7662 | 3975.4694 | 3978.1737 | 3980.8791 | 3983.5856 | 3986.2933 | 3989.0021 | 3991.7120 | 3994.4230 | 3997.1351 | 3.75 |
| 3.76 | 3999.8484 | 4002.5628 | 4005.2783 | 4007.9949 | 4010.7126 | 4013.4315 | 4016.1514 | 4018.8725 | 4021.5947 | 4024.3181 | 3.76 |
| 3.77 | 4027.0425 | 4029.7681 | 4032.4948 | 4035.2226 | 4037.9516 | 4040.6816 | 4043.4128 | 4046.1451 | 4048.8786 | 4051.6131 | 3.77 |
| 3.78 | 4054.3488 | 4057.0856 | 4059.8235 | 4062.5626 | 4065.3027 | 4068.0440 | 4070.7864 | 4073.5300 | 4076.2746 | 4079.0204 | 3.78 |
| 3.79 | 4081.7673 | 4084.5154 | 4087.2645 | 4090.0148 | 4092.7662 | 4095.5188 | 4098.2724 | 4101.0272 | 4103.7831 | 4106.5402 | 3.79 |
| 3.80 | 4109.2983 | 4112.0576 | 4114.8180 | 4117.5796 | 4120.3422 | 4123.1060 | 4125.8709 | 4128.6370 | 4131.4042 | 4134.1725 | 3.80 |
| 3.81 | 4136.9419 | 4139.5533 | 4142.1657 | 4144.7791 | 4147.3934 | 4150.0087 | 4152.6250 | 4155.2422 | 4157.8604 | 4160.4795 | 3.81 |
| 3.82 | 4163.0996 | 4165.7207 | 4168.3427 | 4170.9657 | 4173.5897 | 4176.2146 | 4178.8405 | 4181.4674 | 4184.0952 | 4186.7240 | 3.82 |
| 3.83 | 4189.3537 | 4191.9844 | 4194.6161 | 4197.2487 | 4199.8823 | 4202.5169 | 4205.1524 | 4207.7889 | 4210.4264 | 4213.0648 | 3.83 |
| 3.84 | 4215.7042 | 4218.3446 | 4220.9859 | 4223.6282 | 4226.2715 | 4228.9157 | 4231.5609 | 4234.2071 | 4236.8542 | 4239.5023 | 3.84 |
| 3.85 | 4242.1514 | 4244.8014 | 4247.4524 | 4250.1043 | 4252.7573 | 4255.4111 | 4258.0660 | 4260.7218 | 4263.3786 | 4266.0364 | 3.85 |
| 3.86 | 4268.6951 | 4271.3548 | 4274.0155 | 4276.6771 | 4279.3397 | 4282.0033 | 4284.6678 | 4287.3333 | 4289.9998 | 4292.6672 | 3.86 |
| 3.87 | 4295.3357 | 4298.0050 | 4300.6754 | 4303.3467 | 4306.0190 | 4308.6922 | 4311.3665 | 4314.0417 | 4316.7178 | 4319.3950 | 3.87 |
| 3.88 | 4322.0731 | 4324.7521 | 4327.4322 | 4330.1132 | 4332.7952 | 4335.4781 | 4338.1620 | 4340.8469 | 4343.5328 | 4346.2196 | 3.88 |
| 3.89 | 4348.9074 | 4351.5962 | 4354.2860 | 4356.9767 | 4359.6684 | 4362.3610 | 4365.0546 | 4367.7492 | 4370.4448 | 4373.1414 | 3.89 |
| 3.90 | 4375.8389 | 4378.5374 | 4381.2368 | 4383.9372 | 4386.6387 | 4389.3410 | 4392.0444 | 4394.7487 | 4397.4540 | 4400.1602 | 3.90 |
| 3.91 | 4402.8675 | 4405.5757 | 4408.2849 | 4410.9950 | 4413.7062 | 4416.4183 | 4419.1313 | 4421.8454 | 4424.5604 | 4427.2764 | 3.91 |
| 3.92 | 4429.9934 | 4432.7113 | 4435.4302 | 4438.1501 | 4440.8710 | 4443.5928 | 4446.3156 | 4449.0394 | 4451.7642 | 4454.4899 | 3.92 |
| 3.93 | 4457.2166 | 4459.9443 | 4462.6730 | 4465.4026 | 4468.1332 | 4470.8648 | 4473.5974 | 4476.3309 | 4479.0654 | 4481.8009 | 3.93 |
| 3.94 | 4484.5373 | 4487.2748 | 4490.0132 | 4492.7526 | 4495.4930 | 4498.2343 | 4500.9766 | 4503.7199 | 4506.4642 | 4509.2094 | 3.94 |
| 3.95 | 4511.9556 | 4514.7028 | 4517.4510 | 4520.2002 | 4522.9503 | 4525.7014 | 4528.4535 | 4531.2066 | 4533.9606 | 4536.7156 | 3.95 |
| 3.96 | 4539.4716 | 4542.2286 | 4544.9865 | | | | | | | | 3.96 |

Source : Water Services Department

END OF RATING TABLE NO. 11

## APPENDIX G

**GORDON**

| DATE | TIME | LEVEL | FLOW |
|---|---|---|---|
| 17/7/1989 | 22:15 | 0.710 | 6.79 |
| | 23:15 | 0.740 | 7.34 |
| 18/7/1989 | 0:25 | 0.840 | 9.30 |
| | 1:00 | 0.825 | 9.02 |
| | 2:00 | 0.790 | 8.31 |
| | 3:00 | 0.760 | 7.72 |
| | 5:30 | 2.040 | 34.86 |
| | 7:15 | 1.340 | 19.30 |
| | 8:45 | 2.020 | 34.01 |
| | 9:45 | 2.120 | 38.40 |
| | 11:00 | 1.850 | 28.50 |
| | 12:00 | 1.600 | 24.21 |
| | 13:00 | 1.430 | 21.04 |
| | 14:00 | 1.360 | 19.72 |
| | 15:00 | 1.285 | 18.17 |
| | 16:00 | 1.130 | 15.08 |
| | 17:00 | 1.025 | 13.03 |
| | 18:25 | 0.961 | 11.71 |
| | 19:00 | 1.021 | 12.95 |
| | 20:00 | 1.486 | 22.09 |
| | 20:45 | 1.653 | 25.19 |
| | 21:20 | 1.643 | 25.02 |
| | 22:00 | 1.808 | 27.74 |
| | 23:00 | 2.498 | 59.09 |
| | 23:30 | 2.691 | 71.35 |
| 19/7/1989 | 1:00 | 2.211 | 42.95 |
| | 2:00 | 1.780 | 27.29 |
| | 3:00 | 1.455 | 21.51 |
| | 4:00 | 1.270 | 17.87 |
| | 5:00 | 1.160 | 15.69 |
| | 6:00 | 1.080 | 14.10 |
| | 7:00 | 1.020 | 12.93 |
| | 8:00 | 0.975 | 12.02 |
| | 9:00 | 0.940 | 11.27 |
| | 10:15 | 0.919 | 10.82 |
| | 10:45 | 0.951 | 11.50 |
| | 12:00 | 0.901 | 10.46 |
| | | 50.288 | 778.35 |

**BRENDA**

| DATE | TIME | LEVEL | FLOW |
|---|---|---|---|
| 20/5/1989 | 6:00 | 0.535 | 3.76 |
| | 7:00 | 0.665 | 6.00 |
| | 8:00 | 0.830 | 9.12 |
| | 9:00 | 1.040 | 13.33 |
| | 10:00 | 1.430 | 21.04 |
| | 11:00 | 1.700 | 26.01 |
| | 12:00 | 1.740 | 26.65 |
| | 12:40 | 1.725 | 26.41 |
| | 14:00 | 2.850 | 82.55 |
| | 15:00 | 3.270 | 117.33 |
| | 16:00 | 3.570 | 146.09 |
| | 17:00 | 3.740 | 164.41 |
| | 18:00 | 3.767 | 167.45 |
| | 19:45 | 3.780 | 168.93 |
| | 20:35 | 3.730 | 163.29 |
| | 21:00 | 3.780 | 168.93 |
| | 22:00 | 3.790 | 170.07 |
| | 23:00 | 3.800 | 171.22 |
| 21/5/1989 | 0:00 | 4.046 | [illegible] |
| | 1:30 | 4.355 | [illegible] |
| | 2:00 | 4.275 | [illegible] |
| | 3:00 | 3.945 | 187.43 |
| | 4:00 | 3.620 | 151.32 |
| | 5:00 | 3.505 | 139.45 |
| | 6:15 | 3.585 | 147.64 |
| | 9:20 | 3.340 | 123.49 |
| | 10:30 | 3.565 | 145.57 |
| | 14:00 | 2.500 | 59.22 |
| | | 82.478 | 2606.71 |

TASHA (1990)

| DATE | TIME | LEVEL | FLOW |
|---|---|---|---|
| 30/7/1990 | 15:00 | 0.610 | 5.09 |
| | 17:00 | 0.618 | 5.22 |
| | 18:00 | 0.647 | 5.69 |
| | 19:00 | 0.660 | 5.91 |
| | 20:00 | 0.679 | 6.24 |
| | 21:00 | 0.687 | 6.38 |
| | 22:00 | 0.695 | 6.52 |
| | 23:00 | 0.695 | 6.52 |
| 31/7/1990 | 0:00 | 0.694 | 6.50 |
| | 1:05 | 0.692 | 6.47 |
| | 2:00 | 0.770 | 7.91 |
| | 3:00 | 0.910 | 10.65 |
| | 4:00 | 1.110 | 14.68 |
| | 5:00 | 1.380 | 20.12 |
| | 6:00 | 1.557 | 23.41 |
| | 7:00 | 1.658 | 25.28 |
| | 8:15 | 1.700 | 26.01 |
| | 9:00 | 1.460 | 21.60 |
| | 10:00 | 1.280 | 18.07 |
| | 11:00 | 1.200 | 16.49 |
| | 12:00 | 1.090 | 14.29 |
| | 13:00 | 1.026 | 13.05 |
| | 14:00 | 0.976 | 12.04 |
| | 15:00 | 0.936 | 11.18 |
| | 16:00 | 0.905 | 10.55 |
| | 17:40 | 2.155 | 40.08 |
| 1/8/1990 | 0:00 | 0.945 | 11.37 |
| | 3:00 | 0.870 | 9.91 |
| | | 28.605 | 367.23 |

NATHAN

| DATE | TIME | LEVEL | FLOW |
|---|---|---|---|
| 16/6/1990 | 15:00 | 0.660 | 5.91 |
| | 16:00 | 0.655 | 5.83 |
| | 17:00 | 0.703 | 6.66 |
| | 18:00 | 0.760 | 7.72 |
| | 19:00 | 0.810 | 8.71 |
| | 20:00 | 0.846 | 9.46 |
| | 21:00 | 0.920 | 10.85 |
| | 22:00 | 1.520 | 22.73 |
| | 22:45 | 1.548 | 23.25 |
| | 23:45 | 1.478 | 21.94 |
| 17/6/1990 | 0:25 | 1.482 | 21.94 |
| | 2:15 | 1.319 | 18.87 |
| | 3:00 | 1.359 | 19.70 |
| | 3:45 | 1.649 | 25.12 |
| | 5:15 | 1.533 | 22.97 |
| | 6:00 | 1.653 | 25.19 |
| | 7:00 | 1.703 | 26.05 |
| | 8:00 | 1.993 | 32.88 |
| | 9:00 | 2.555 | 62.66 |
| | 10:00 | 2.500 | 59.22 |
| | 10:30 | 2.510 | 59.84 |
| | 11:00 | 2.463 | 56.97 |
| | 12:00 | 2.203 | 42.53 |
| | 13:00 | 1.933 | 30.43 |
| | 13:30 | 1.893 | 29.37 |
| | | 38.648 | 656.80 |

TASHA (1993)

| DATE | TIME | LEVEL | FLOW |
| --- | --- | --- | --- |
| 20/8/1993 | 3:00 | 0.711 | 6.80 |
| | 4:00 | 0.721 | 6.99 |
| | 5:00 | 0.735 | 7.25 |
| | 6:00 | 0.753 | 7.71 |
| | 7:00 | 0.795 | 8.41 |
| | 8:00 | 0.960 | 11.69 |
| | 9:00 | 1.110 | 14.68 |
| | 10:00 | 1.250 | 17.47 |
| | 11:00 | 1.330 | 19.10 |
| | 11:45 | 1.347 | 19.45 |
| | 20:00 | 1.290 | 18.27 |
| | 21:00 | 1.460 | 21.60 |
| | 22:00 | 1.710 | 26.17 |
| | 23:00 | 1.860 | 28.70 |
| 21/8/1993 | 0:00 | 2.030 | 34.43 |
| | 1:00 | 2.250 | 45.01 |
| | 1:45 | 2.300 | 47.72 |
| | 13:00 | 2.150 | 39.83 |
| | 16:00 | 2.140 | 39.34 |
| | 21:00 | 2.050 | 35.29 |
| 22/8/1993 | 6:00 | 1.893 | 29.37 |
| | 10:00 | 1.840 | 29.30 |
| | | 32.685 | 514.58 |